A Manual for Planning Structural Control of Avalanches

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ROCKY MOUNTAIN FOREST AND RANGE EXPERIMENT STATION
RAYMOND PRICE, DIRECTOR FORT COLLINS, COLORADO
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PREFACE

This Manual supplements "Avalanche Control in the Starting Zone -- Guidelines for the Planning and Design of Permanent Supporting Structures," Swiss guidelines translated by Hans Frutiger, and published by the Rocky Mountain Forest and Range Experiment Station in 1962 as Station Paper No. 71.

The accepted European symbols and the metric system have been used in this Manual to permit easier checking with the information already published by the Rocky Mountain Station on avalanche control. The following conversions may be helpful:

1 meter (m.)	= 39.37 inches or 3.28 feet
1 hectare (ha.)	= 2.471 acres
1 ton or tonne (t.)	= 1,000 Kg. or 2,200 pounds
tg	= tangent of an angle

Force has been expressed as metric tons per running meter (t/m'), or as metric tons per square meter (t/m^2).

1.0 t/m' = 671 pounds per foot

1.0 t/m^2 = 206 pounds per square foot, or
1.4 pounds per square inch (p.s.i.)

Snow density is expressed in several units that are related as follows:

$0.100\ t/m^3 = 100\ Kg/m^3 = 0.10\ g/cm^3 = 10$ percent

The symbols used for forces and pressures are identical in the Manual and in the Guidelines:

Capital letters (for example, R)	= total force on a structure or part of a structure
Capital letters, primed (for example, R')	= force per unit length ($R = R' \cdot l$)
Lower-case letters (for example, q)	= load per unit area or pressure

Exceptions to the above rules are the forces p_B, q_B, q_S, acting on the bars of a grate and the swivel post of a snow net.

Then:

Lower-case letters with capitalized subscript (for example, p_B)	= load per unit length

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by

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INTRODUCTION

Regardless of the type of avalanche control employed, certain things are essential to the success of any such venture. First, detailed information on weather and snow conditions, and on the frequency and size of avalanches, must be available for each specific area to be controlled. These data usually can be obtained only by field observations in the avalanche zone. Second, once the structures are installed, routine field checks, in winter as well as in summer, are needed to determine whether alterations are needed in the original project layout, and to keep the structures in good repair. Sometimes changes in the snow cover are brought about by the structures themselves. Finally, continued research is needed to learn more about the basic physical and mechanical properties of the snow cover in steep terrain, and how modern engineering techniques can be used to give the most effective control system at the lowest cost.

This Manual should be considered a first edition that may be refined and expanded later if a comprehensive handbook is desired. Most of the field work in the United States was done in 1961-62 in the Colorado Rocky Mountains, but the techniques and procedures are applicable to most avalanche areas, and are based on many years of experience with avalanche control structures in Europe.

The Manual is divided as follows: PART I gives a classification of avalanches based on the features important for structural control, and explains how structures and forests can be used to control avalanches. PART II outlines the type of data needed to plan an avalanche control project, how to gather the information, and the type, arrangement, and design of structures. PART III is a case study of the Stanley Avalanche near Berthoud Pass, Colorado; it is an example of how data are used to develop an avalanche control project for a specific area. Since many of the statements made in Part III are based on only 1 winter's observations (1961-62), they should be considered tentative until more extensive field data are available. The APPENDIX contains the English translations of pertinent articles by Roch (1964), Schwarz (1960), and Frutiger and de Quervain (1964).[4] NOMOGRAPHS of four important formulas are in a pocket inside the back cover.

In 1962, Frutiger translated from German to English the Swiss guidelines and specifications for building permanent structures in the starting zones of avalanches (Swiss Federal Institute for Snow and Avalanche Research 1961). His translation of "Avalanche Control in the Starting Zone--Guidelines for the Planning and Design of Permanent Supporting Structures" was published by the Rocky Mountain Forest and Range Experiment Station as Station Paper 71. The present Manual supplements Station Paper 71, gives the reasoning and background information for many of the specifications set forth in the Guidelines, and presents data on other types of avalanche control structures. Most explanations and background material were intentionally omitted from the Guidelines for the sake of brevity.

The Guidelines cover only supporting structures in the starting zone because this is the most important type of structural control for avalanches in Switzerland. Because there is no way of knowing what type of control will be most effective or economical in other countries, however, all techniques used in avalanche control are summarized herein (Part I, Sect. 2, 3). In this way a comprehensive evaluation of structural control of avalanches can be based on knowledge of all the possibilities.

Complete definitions of all the special terms used in structural control are not given in this Manual, since they are available elsewhere (Seligman 1936, Bader et al. 1939, U.S. Forest Service 1961, Swiss Federal Institute for Snow and Avalanche Research 1961).[5]

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[4] *Names and dates in parentheses refer to Literatude Cited, p. 60.*

[5] *Mellor, Malcolm. Cold regions science and engineering. Part III, Sect. A3d. Avalanches. U. S. Army Materiel Command, Cold Regions Res. and Engin. Lab., Hanover, N. H. (In press.)*

It seems likely that structural avalanche control in the United States will follow a slightly different route from that developed in Europe. Here, because cheap manpower is not available in mountainous areas, the trend will favor structures that can be built with heavy machinery and a minimum of hand labor -- retarding and catching structures in the runout zone and the direct-protection structures such as avalanche sheds. Until this country's engineers gain experience and confidence, avalanche control projects based on supporting structures in the starting zone will probably be confined to easily accessible avalanches which threaten valuable property or heavy concentrations of people.

The avalanche control project started in 1963 by the Climax Molybdenum Company of Climax, Colorado, is a case in point: here, supporting structures were installed in the starting zone of a small avalanche that threatened buildings where many people and expensive machinery were housed. This is thought to be the first major avalanche control project in the United States to use supporting structures in the starting zone (fig. 1).

A survey was made of 80 avalanche paths along four major highways in Colorado to determine the possibilities for structural control (Frutiger 1964). Supporting structures were considered the obvious solution in 37 cases, and a possible solution in 15 more. Direct-protection structures were recommended for 15, and structural controls in the track or runout zone for 7. Structural control was not recommended for the remaining six paths.

Figure 1.--Avalanche control structures in starting zone of a small avalanche that threatens a mining operation near Climax, Colorado, A, summer view, shows height and location of structures; B, winter scene, illustrates uneven distribution of snow; C, a large earthen dam built farther downslope where slope is more gentle, crosses avalanche path to stop any avalanches that started below structures. More structures have been added in starting zone since these pictures were taken in October 1963.

PART I.

AVALANCHE CLASSIFICATION AND THE ROLE OF STRUCTURES AND FORESTS IN AVALANCHE CONTROL

1. Avalanche Classification for Structural Control Purposes

A description and classification of avalanches for structural control purposes will differ from that developed for basic research in the science of snow and avalanches such as given by de Quervain (1957), Seligman (1936), and the U. S. Forest Service (1961). Frequency of occurrence, for example, is completely neglected in the scientific classification, yet it is highly significant for planning structural avalanche control (figs. 2, 3).

The distinction between loose-snow and slab avalanches is only significant for control measures in the starting zone. This distinction is not important for diversion or other protective structures in the track and runout zone because, once moving at full speed, both of these dry-snow types look and behave exactly the same. The more important distinction, therefore, would be whether it is a dry-snow or a wet-snow avalanche, and whether it occurs frequently. Naturally, in a given area, all kinds of avalanches occur; but for structural control, it is important to find out which type is the most significant.

Schaerer (1962a, 1962b) also classified avalanches for structural control purposes.

Figure 2.--Aspen on a site where the climax forest is fir and spruce often indicates an avalanche zone. The aspen in the foreground undoubtedly are growing in the runout zone of an avalanche that many years ago destroyed the spruce-fir stand. A narrow path has been cut through the aspen stand by a recent small avalanche. The age of the aspen would indicate the date of the last big avalanche. One of the Jones Brothers avalanches, Jones Pass, Colorado. May 10, 1962.

Figure 3.--The aspen in the foreground had been growing on this site for at least 40 years. During the winter of 1961-62 they were knocked down by an avalanche. This vividly illustrates that long periods of inactivity are no assurance that certain avalanche areas are safe. Such avalanches have been called erratic because they run only under certain rather unusual conditions. The man near the right margin gives an impression of the size of the trees. West avalanche of Kendall Mountain near Silverton, Colorado. July 4, 1962.

His "dry-snow direct-action avalanche" corresponds to the "loose-snow avalanche" classification used in this report, his "dry-snow delayed-action avalanche" to the "slab avalanche," and his "spring-thaw avalanche" to the "spring or wet avalanche." His "wet-snow direct-action avalanche" is not significant in the Rocky Mountains of Colorado.

1.1 Loose-snow Avalanches

Loose-snow avalanches involve layers of snow with little or no internal cohesion. They start from a point or a very small area, and involve a formless mass of snow. The line between the snow that stayed in place and that that slid away is indefinite. On the basis of tests and observations of modern control structures in the European Alps for the past 15 years, this kind of snow movement appears to give the most trouble for avalanche control in the starting zone.

In the early days of snow and avalanche research, too little attention was given to the possibility of loose-snow slides. A theory of snow-cover stabilization, based on the slab-type avalanche -- the most dangerous type for skiers -- did not give enough consideration to the loose-snow avalanche. According to the slab-avalanche theory, the snowpack can be anchored to the ground by only a few structural "elements." This was the reason that some European avalanche control projects were installed with a minimum number of structures which were very widely distributed in a discontinuous, staggered arrangement, with large gaps left between the crossbeams of the structures. Experience has shown that these control works are not able to prevent the start of loose-snow avalanches. Furthermore, once started, the snow could not be stopped by the supporting planes of the structures; it flowed through the grate like water. Such slides, running between the structures, gained enough speed to turn into destructive avalanches.

Only a few people have had the chance to observe loose-snow avalanches. They occur on very steep, irregular slopes, and often start during or soon after snowstorms while the snow is still fluffy. Since there is no fracture line, it is difficult to locate the starting zone; a loose-snow slide can often be identified only by the damage it has caused to structures. Unfortunately, they have to be expected in any control area where steep slopes are present, and enough structures must be provided to stop them at their origin. Loose-snow avalanches are the reason why so many structures have to be installed. The width of the opening between crossbeams, the intervals between adjacent structures in the same line, and the distance between two lines of structures have to be kept within certain limits to control loose-snow avalanches.

1.2 Slab Avalanches

Slab avalanches involve layers of snow with decided internal cohesion. The sliding snow breaks away from the stable snow along a distinct fracture line -- a useful indicator of the starting zone.

Slab avalanches, also called simply "slabs," are the most common type, and usually start after a fresh snowfall has had a chance to settle and become more cohesive. Avalanche control in the starting zone would be much easier if only slabs were expected because, once a slab has formed, the snow cover has enough strength to support itself for a certain distance around each anchor point. The snow-pressure theory, developed by Haefeli (Bader et al. 1939) and Bucher (1948), is based on the idea that large forces can be transmitted within the snow cover. The cohesiveness of the snow cover permits Haefeli (Bader et al. 1939, p. 192 of Transl. 14) to state:

> From the viewpoint of construction and statics, the breaking up of a continuous supporting wall into separate elements leads in general to a higher concentration of the forces. The use of high-class materials thus permits a better utilization of their properties, and at the same time reduces surface weathering.

In other words, a relatively few, strong structures in an interrupted or discontinuous arrangement would be adequate for control and would be cheaper than continuous structures.

Either the dry, loose-snow avalanche or the slab can become a dust avalanche (airborne, powdery avalanche) if it reaches full speed in a track that is long and steep. The distinction between the dust avalanche and the wet-snow avalanche becomes important for control structures built in the track. It is very difficult to control airborne avalanches in the track. The Twin Lakes Avalanche on January 21, 1962, near Twin Lakes, Colorado, was an excellent illustration of the jumping power of a dry-snow avalanche moving at full speed.[6] About midway down its track this avalanche jumped a natural terrain barrier 100 feet tall.

1.3 Spring or Wet Avalanches

Spring or wet avalanches involve layers of wet snow with little cohesion. Like dry, loose-snow avalanches, they leave no sharp fracture line. Avalanches of wet snow move slowly but have great destructive power because of their weight.

Although this type of avalanche can be controlled easily in the track if terrain conditions are favorable, this does not help much when other types of avalanches also run in the same track. The spring or wet-snow avalanche flows along the ground at a low speed, and can be directed. Because it runs slowly, it does not travel far into the runout zone, and normally stops at the beginning of the transition zone between the lower end of the track and the beginning of the runout zone.

1.4 Important Parts of an Avalanche Area

For a discussion of avalanche control structures, the four parts of an avalanche area must be distinguished: catchment basin, starting zone, track, and runout zone (figs. 4-8, 21).

1.41 Catchment Basin

The top part of an avalanche area is called the catchment basin. Often it lies above timberline on bowl-shaped, steep slopes where heavy winds cause deep snow accumulations (see fig. 27). In other cases, it may be a broad, uniform area with few distinguishable terrain features (fig. 4).

1.42 Starting Zone

The actual places within the catchment basin where avalanches start are called starting spots or the starting zone. The area of the starting zone is less than the total area of the catchment basin. The starting zone of a slab avalanche shows a pronounced, well-defined fracture line; hence, the starting zone is also called the "fracture zone." Long-term observations show that the fracture lines of specific avalanches appear in the same general area year after year. Such observations are needed to delineate the starting zone of a particular avalanche. The fracture lines of many avalanches lie near the roll of snow that forms just to the lee of the steep alpine rimlands. Downhill from the roll there is a steep scarp where the snow normally fractures.

On irregular slopes, the fracture zones lie on the convex parts of the slope. In these transition zones, where the slope suddenly steepens, creep within the snow cover produces tensile stresses which eventually cause fracture.

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[6] *Frutiger, Hans. Avalanche zoning. 1962. (Unpublished report on file at the Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado.)*

Figure 4.--A typical areal or unconfined avalanche. The track is as wide as the starting zone. This avalanche occasionally crosses the 1,100 feet of flat valley behind the lake and reaches the highway. Ironton Park Avalanche on Red Mountain Pass, Colorado. July 3, 1962.

Figure 5.--The spruce and fir stand is not dense enough to prevent avalanches. It is difficult to locate the starting spots and tracks of this type of areal or unconfined avalanche. Floral Park Avalanche, Berthoud Pass, Colorado. April 25, 1962.

Figure 6.--Fracture spot at the border of an opening in the stand of young trees. One tree is tilted down by moving snow. Stick indicated by arrow is 1 meter long. Floral Park Avalanche, Berthoud Pass, Colorado. April 25, 1962.

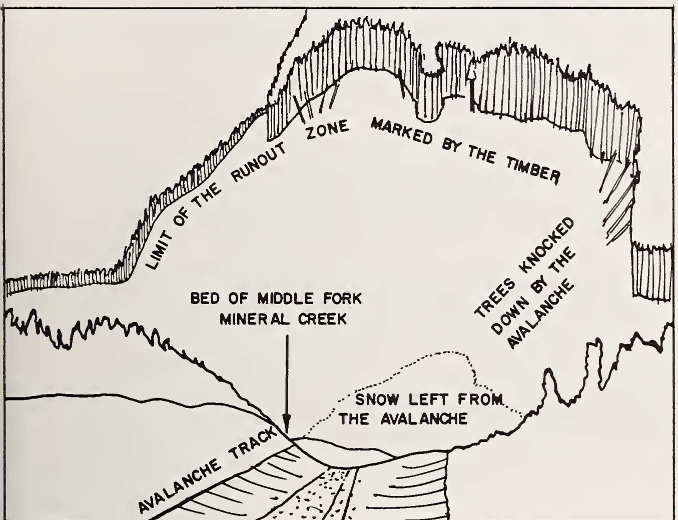

Figure 7.--How far does the runout zone extend? Vegetation is a good indicator of the limits of the runout zone. This avalanche hit the bottom of Mineral Creek valley while moving at full speed and stopped abruptly. The zone influenced by the avalanche extends 500 feet (150 m) from the creek up the opposite slope. Ophir Pass East, No. 3; 1 mile west of Burro Bridge. July 3, 1962.

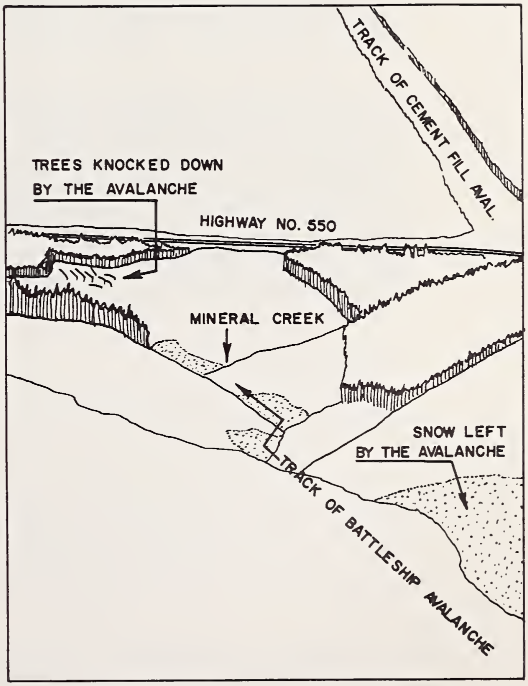

Figure 8.--The runout zone of Battleship Avalanche extends from the valley 525 feet (160 m) up the opposite slope with a vertical rise of 240 feet (75 m). (See figure 21.) Battleship Avalanche, Red Mountain Pass, Colorado. July 3, 1962.

On irregular slopes the fracture zones lie on the convex parts of the slope. In these transition zones, where the slope suddenly steepens, creep within the snow cover produces tensile stresses which eventually cause fracture.

Some starting zones are well defined and easily located, as illustrated by the Stanley Avalanche, which has a starting zone well defined by the terrain (see fig. 27). Other starting zones are rather poorly defined; it is not at all obvious where the avalanches start, and long-term, detailed winter observations are needed to locate the spots to be controlled. The Ironton Park and Floral Park Avalanches (see figs. 4-6) are examples of this type.

The extent of the starting zone varies from little spots to widespread areas. The area of the starting zone determines how many supporting structures will be needed to control the avalanche as well as the cost of a control project.

Slopes steeper than 62 percent should be considered avalanche prone. The steepest slope that can be controlled is about 120 percent; cliffs cannot be controlled. Irregular and rugged terrain is difficult to control. Slopes between 30 and 62 percent are especially troublesome when planning avalanche control for villages and other critical areas. Often such slopes have no avalanches for decades, and the people become overconfident and careless. Wechsberg (1958) relates the story of several such catastrophes.

1.43 Avalanche Track

When first released, snow masses flow in a shallow layer and follow any depression in the slope; as momentum increases, the snow often concentrates in gullies, couloirs, or other marked paths. The path the avalanches usually follow is called the avalanche track.

Where the track is well defined, the avalanche will follow the same track every time. These are called <u>channeled</u> avalanches. When the slope is more or less uniform, the snow masses may take different routes or they may spread out over a wide area. These are <u>unconfined</u> avalanches or avalanches with an indefinite track. The track of an unconfined avalanche can be as wide as the starting zone (see fig. 4). On tracks that are not definite, the dust avalanche is very hazardous because it does not follow any set path and may come down where it is not expected. On the other hand, a wet-snow avalanche always follows the same track. Different types of avalanches coming down the same mountain may follow different paths according to their flow mechanism. The track of the airborne, dust avalanche is more or less straight while the damp avalanche follows every curve of the gully.

1.44 Runout Zone

The zone where avalanches naturally stop is called the runout zone. The terminus of avalanches in the same track varies, depending on the size and type of avalanche. The lower limit of the runout zone may not be reached for several years, but under extreme conditions, a big avalanche will go much farther than might be expected. Terrain features typical of runout zones are: (1) the lower end of an avalanche slope where the slope becomes more gentle, (2) the alluvial fan of a gully, and (3) the flat valley floor. In special cases the runout zone can extend part way up the opposite slope (see figs. 7-8). On cone-shaped alluvial fans, the paths of avalanches are indefinite; the direction of the avalanche may be changed by wind or earlier snow deposits.

The zone of influence of an avalanche is not limited to the physical borders of the track and runout zone. The air pressure wave, called the avalanche blast, may cause damage in a wide area. All the surroundings that are under the influence of the avalanche blast belong to the runout zone. Because houses and highways often lie in this danger zone, it deserves special attention.

2. Avalanche Control by Means of Structures

2.1 Short History of the Use of Structures in Europe

Although many European mountain settlements could not exist without some type of avalanche control, the need to reestablish protective forests devastated by logging, fire, and overgrazing was the biggest incentive for intensive avalanche control in the Alps. In Switzerland, a law was passed in 1876 permitting federal financial aid for the reestablishment of protective forests. This made the first large-scale avalanche control projects possible. About the same time, forestry agencies in France and Austria began working in the field of avalanche control. Many different techniques were soon developed.

In the early days, barriers were built from materials found in place. Above timberline, control works were almost exclusively earth terraces, earth terraces with small dry-masonry footings, and dry-masonry walls. Below timberline, wooden poles were often driven into the ground in a checkered arrangement to protect young afforestations. Simple fences, rakes, and bridges built of round timber were also used. Some of these early avalanche control works were so well done that nobody speaks of them today because the avalanches were stopped, the forests reestablished, and it now seems impossible that it was ever otherwise.

The empirical approach gave way to the scientific study of snow and avalanches with the establishment of the Swiss Avalanche Research Commission in 1932, and the later development of the Swiss Federal Institute for Snow and Avalanche Research at Weissfluhjoch near Davos. A great deal of progress was made in the following years. Skiers started to make observations in areas previously considered inaccessible, and laid a foundation for many of the scientific studies to follow (Seligman 1936). Older types of structures were modified and improved, and useful theories of snow movement and pressures were developed.

After the disastrous avalanche winter of 1950-51, a new era began in avalanche control. Structures built with modern building materials were used almost exclusively. In the fall of 1950 the first snow nets were installed. They were made of wire rope netting, and were supported by wooden poles. The next year the first aluminum snow bridges were constructed. At the same time, a concrete company made the first attempt to build snow bridges from prestressed concrete members. In 1955, an Austrian steel company in collaboration with the Austrian Avalanche Control Service brought out an all-steel snow bridge that was used extensively in Austria (Hanausek 1960), and was also installed in some Swiss projects. In 1957, the Electricité de France (EDF) used nylon nets for avalanche control. The nets were manufactured by a company that produced nylon nets for stopping airplanes on aircraft carriers.[7]

These modern structures have almost completely replaced the older ones because of the rising cost of manual labor. In recent projects three types of supporting structures, namely bridges, rakes, and nets, are commonly used (figs. 9-15). Masonry walls and terraces are still being used, but mostly for special purposes.

In 1961, a set of "Guidelines" (Swiss Federal Institute for Snow and Avalanche Research 1961) were published to cope with the complexities of design, layout, and arrangement of the new structures. Today there are about 3,000 avalanche control projects in Switzerland, and many others in Austria and France. Most of these projects use structures in the starting zone, following the motto "it is best to fight the root of evil."

It is surprising that a similar development did not take place in the mountainous areas of North America. During the mining era, the Rocky Mountains, Sierras, and Cascades were densely populated, and history gives an account of several avalanche disasters (Hult 1960). Perhaps the mining settlements did not last long enough for the need of avalanche protection to be fully realized.

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[7] *Aerazur Constructions Aeronautiques, Paris. Resultats pratiques acquis par les filets paravalanches en nylon depuis 1957 [Practical results gained by avalanche nylon nets since 1957]. Personal correspondence and office report, September 26, 1961.*

Figure 9.--Crude snow rake (upper left) made of round timber usually used in the afforestation zone. Kühnihorn, St. Antönien-Castels, Switzerland. April 2, 1959.

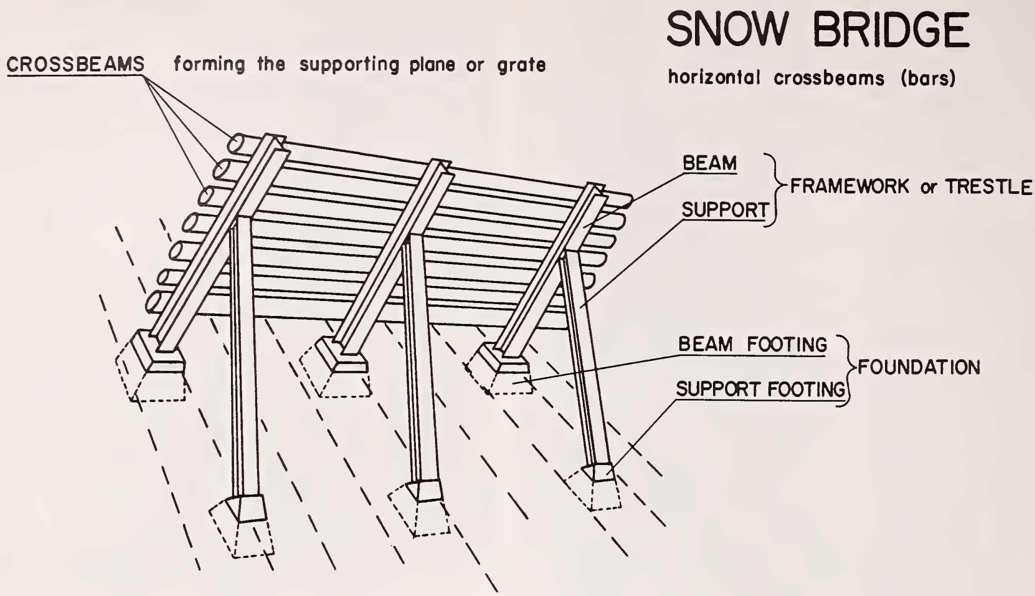
Figure 10.--Snow bridge (above) made of steel tubes and I-beams. Wilerhorn, Brienzwiler, Switzerland. August 11, 1960.

Figure 11.--Snow rake (lower left) made of aluminum. Wilerhorn, Brienzwiler, Switzerland. August 11, 1960.

Figure 12.--Snow bridge (above) is made of prestressed concrete. Kühnihorn, St. Antönien-Castels, Switzerland. April 2, 1959.

Figure 13.--Snow net (upper right) made of wire rope. Individual nets are triangular in shape and are hung on tubular steel posts that have a swivel joint at the bottom. Kneugrat, Braunwald, Switzerland. February 20, 1963.

Figure 14.--Snow net (lower right) made of wire rope on simple, round timber swivel posts. This type has been used successfully for protection of afforestations. Schilt, Stein (Toggenburg), Switzerland. July 14, 1959.



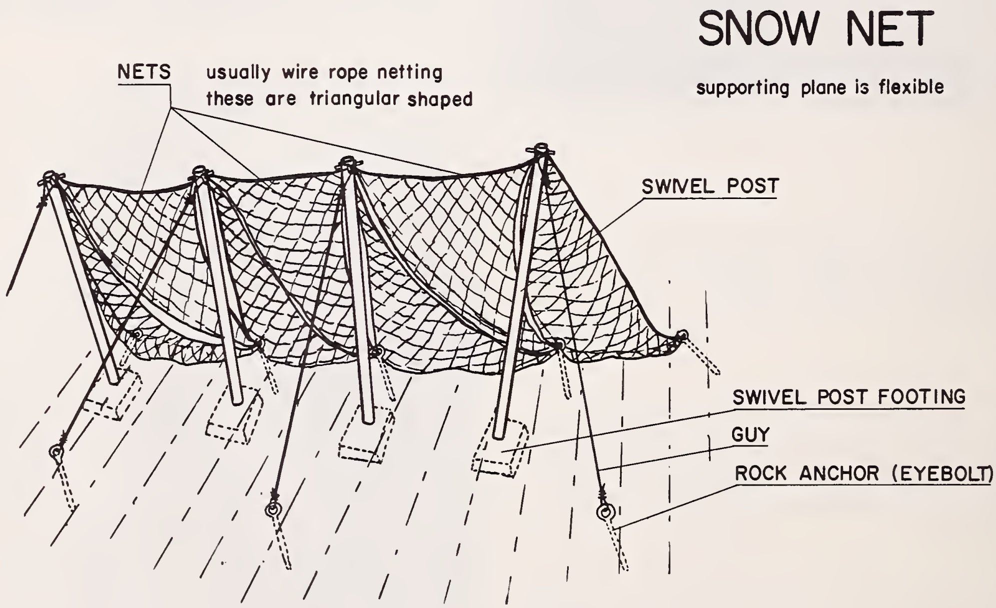
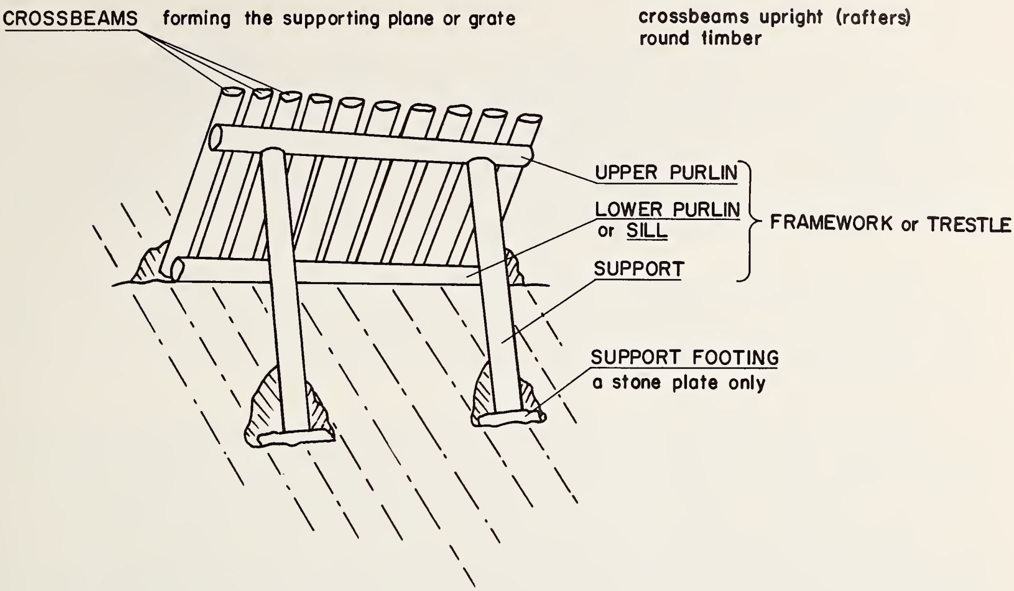


Figure 15.--Open supporting structures with various parts identified.

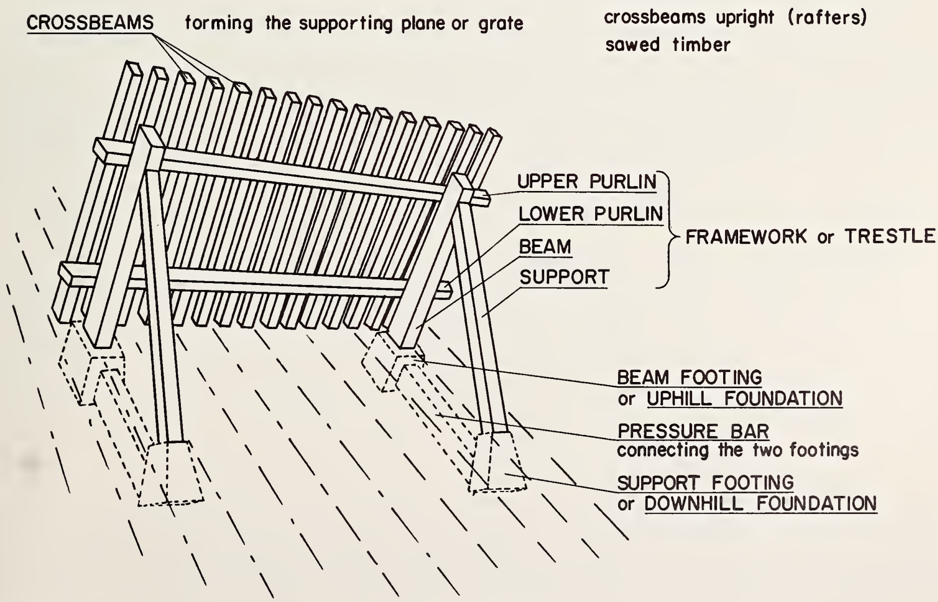
SNOW RAKE

crossbeams upright (rafters)
round timber



SNOW RAKE

crossbeams upright (rafters)
sawed timber



2.2 Supporting Structures in the Starting Zone

2.21 Purpose and Type

The purpose of avalanche control in the starting zone is to reduce the mass of avalanching snow to tolerable amounts and frequencies. How much avalanching can be tolerated must be decided for each avalanche control project. Toleration levels vary; greatest protection is needed for ski areas, roads, railroads, and permanent homes and villages. The Guidelines and this Manual give minimum acceptable levels of protection; these will be inadequate for exceptional conditions. Engineers familiar with design-storm concepts for planning bridges, culverts, and flood control projects know that complete protection for all weather conditions is extremely expensive and can seldom be attained.

Different classes of control structures are used in different parts of an avalanche zone. Supporting structures in the starting zone stabilize the snow cover by splitting up the tensile zones within the snowpack, and by holding the snow in place or reducing its movement to minor proportions. The primary purpose is to keep slab avalanches from starting and to stop loose-snow avalanches within a short distance.

There are many types of supporting structures capable of stabilizing the snow in the starting zone. Modern types, which include snow nets, snow rakes, and snow bridges (figs. 9-15), are made of steel, concrete, wood, or aluminum, and are called "open" or "framed" structures. Older structures were mostly massive terraces and walls.

The crossbeams of an open supporting structure form a plane, called the grate, which supports the snowpack. The crossbeams and the gaps between them can vary in width. A grate is, therefore, more or less penetrable to the snow, depending on the kind of crossbeams and the size of the gaps. The degree of penetrability of a grate can be expressed in terms of the density of the grate, that is, the ratio between the surface of the grate filled with structural material and the total surface of the grate. The flexible supporting plane of a snow net, for example, has an extremely low density. In contrast, the density of a masonry wall (massive structure) is one which signifies no airgaps.

The members of a supporting structure have to be designed to withstand the assumed snow-pressure forces. Because the snow pressure increases with the square of the snow depth, an empirical upper limit of 16 to 20 feet (5-6 m.) has been put on the height of these structures. Experience has also shown that inclining the grate downhill about 15 degrees from the perpendicular to the slope gives a better distribution of the forces acting on the members, especially the uphill footings. Vertical height (H_K) of the structure varies with the steepness of the slope (fig. 16). The slant height (B_K) of a structure is considered to be the significant and appropriate dimension for comparing the costs of different types.

The same slope effect made it necessary to give some standards in the Guidelines for snow nets. Because of the slack in these flexible structures, it was necessary to decide what would be considered the slant height of a net. In addition, it was necessary to define the length of the nets as the arithmetic average of the top and the bottom lengths because the supporting plane of a net is made up of a series of equilateral triangles arranged side by side. This results in the top of the supporting plane being shorter than the bottom. Nets were especially developed to provide light, flexible structures for use in steep, rugged, and barely accessible terrain where transportation of heavy structural parts would be difficult.

The joints between the major members of open, rigid structures may be either hinged or fixed. As a rule, the joint between the beam and the support is hinged (see fig. 15). Even experts do not agree, however, on the best type of joint to connect the superstructure (trestle, framework) to the foundations (footings). This point is too involved to discuss in this paper. For nets, the joint between the swivel post and the swivel post footing is either a universal or a ball-and-socket joint.

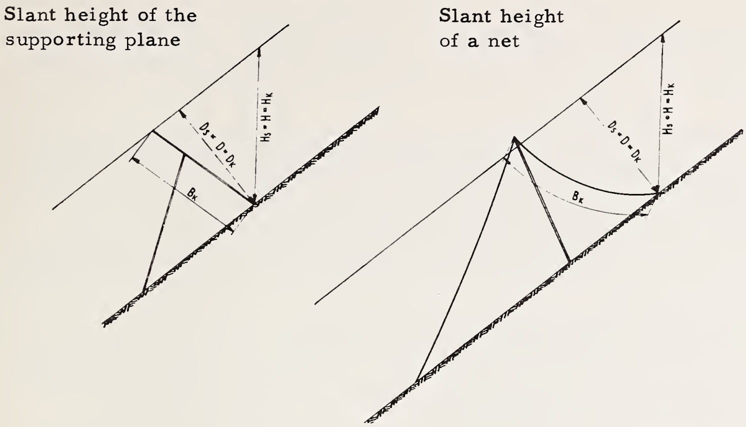


Figure 16.--The slant height (B_K), effective height (D_K), and vertical height (H_K) of rigid and flexible supporting structures.

2.3 Stresses Acting Upon Supporting Structures

2.31 Dynamic Stresses: Shocks and Impacts

Supporting structures are planned and arranged to minimize the movement of snow within the control area. It would be too expensive, however, to install enough structures to prevent all movement of the snow cover. The conventional distance between two lines of structures is 50-65 feet (15-20 m.). Even then, slides occasionally develop between the lines of structures, especially during snowstorms. Several times, slides of fine-grained, cohesionless snow have been observed in Swiss avalanche control areas. Loose-snow slides may flow through the grate of supporting structures and through the interval between two neighboring structures; even slab avalanches can start between lines of structures.[8]

It has been amply demonstrated that open, supporting structures cannot stop an avalanche traveling at full speed. The top row of supporting structures should therefore be very close to the uppermost fracture line. This row of structures must be installed within two or three times the vertical height of the structures below the upper fracture line. Some European projects have had to be completely rebuilt because of severe damage in places where too few structures were installed in an attempt to save material.

2.32 Static Stresses: Creep and Glide Pressure

2.321 Factors Influencing Snow Pressure.--Haefeli, who conducted the first experimental investigation on snow pressure, developed a general theory of the stresses acting in a snowpack on a slope (Bader et al. 1939, pp. 59-218 of Transl. 14), and presented a tentative formula for calculation of snow pressures. Nine years later, Bucher (1948) also developed a formula for the calculation of snow pressure; the two formulas give about the same results.

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[8] *Frutiger, Hans. Eine Beobachtung über das Gleiten der Schneedecke im Bereich einer Erdterrasse. Int. Bericht 365, 11 april 1961. Eidg. Inst. für Schnee- und Lawinenforschung, Weissfluhjoch/Davos, Switzerland. [An observation on the gliding of a snowpack in the vicinity of an earth terrace. Unpublished report 365, Swiss Fed. Inst. for Snow and Avalanche Res.]*

In the Guidelines (Art. 27), the following formula derived from Haefeli's work is used:

$$\boxed{S'_N = \gamma_S \cdot \frac{H_S^2}{2} \cdot K \cdot N} \qquad (27)$$

S'_N component of snow pressure parallel to the slope per unit length of the supporting plane

γ_S average density of the snowpack (varies with the altitude and the aspect of the slope)

H_S snow depth measured vertically

K creep factor (a function of the angle of slope ψ and the snow density γ_S, as shown in the table below)

N glide factor (refers to the glide pressure and varies with the roughness of of the ground surface and the aspect of the slope)

Creep factor K as a function of γ_S and ψ

γ_S (kg/m³):	200	300	400	500	600
K/sin 2ψ:	0.70	0.76	0.83	0.92	1.05

To obtain the approximate values of K corresponding to the snow density, the given values $K / \sin 2\psi$ are multiplied by the values for $\sin 2\psi$.

Snow density at the time of maximum snow depth is fairly constant, and is assumed to be 270 kg/m³ for an altitude of 1,500 m. mean sea level, and an exposure of WNW-N-ENE. From the above table the creep factor, K, for a snow density γ_S of 270 kg/m³ and a slope angle, ψ, of 100 percent (45°) is found to be 0.74.

Substituting this in the formula gives:

$S'_N = 0.27 \times \frac{H_S^2}{2} \times 0.74N$ or approximately $S'_N = 0.10 \times H_S^2 \times N$

General increase in snow density with altitude is computed by multiplying the right side of the above equation by the altitude factor, f_C, shown below:

Altitude above sea level	Altitude factor, f_C	Altitude above sea level	Altitude factor, f_C
<1,500	1.00	2,100	1.12
1,500	1.00	2,200	1.14
1,600	1.02	2,300	1.16
1,700	1.04	.	
1,800	1.06	.	
1,900	1.08	3,000	1.30
2,000	1.10	>3,000	1.30

This gives a relatively simple formula for snow pressure based only on easily determined factors. The above example has been developed for European conditions; a similar one can be developed for Rocky Mountain altitudes as data are collected.

Snow depth is the primary factor in determining snow pressure, since pressure varies as the second power of snow depth. Determining the depth and distribution of the snowpack is most important when an avalanche control area is being investigated. How to collect and analyze these data are discussed in Part III.

2.322 Creep and Glide of the Snow Cover. --Special attention must be given to the creep and glide movements of the snow cover. Unlike snow density, they vary greatly depending on the climate and the exposure of the slope, and the surface roughness at the site.

Haefeli gives a detailed description of his investigations on snow creep made during the winter of 1936-37 in the region of the Weissfluhjoch, Switzerland (Bader et al. 1939, p. 139 of Transl. 14). He used ping-pong balls as floats instead of a sawdust column.

In 1946, In der Gand (1954, 1957, 1959) started an intensive study of glide in connection with studies of the growth of young larch in the starting zone of avalanches. This work is being done in the test fields on the Dorfberg near Davos, Switzerland.

Frutiger investigated the creep and glide of the snow cover near supporting structures and terraces in the avalanche control projects at Mattstock near Amden,[9] [10] and at Kühnihorn near St. Antönien,[11] both in Switzerland. Martinelli (1960) published the results of some investigations on the creep and settlement of the snowpack made in the Rocky Mountains near Loveland Pass, Colorado.

The results of these investigations give only a rough idea, however, of what may happen in the snow cover during its evolution. In the case of an avalanche control project, the creep and glide factors must be determined in the control area. As stated above, the glide factor, especially, depends on weather and local ground-cover conditions. Extreme gliding has been observed several times during October and November in the Swiss Alps when heavy snow fell on the still-warm ground surface. Gliding is generally pronounced on south-facing slopes and on smooth, grassy surfaces. A dense stand of sedges on a steep slope soaked with melt water creates the worst possible conditions. Glide within the snowpack can be detected from the rifts that form in the area of greatest movement. Rifts in the snow cover are always an indication of extreme gliding.

2.33 The Different Aspects of Dynamic and Static Stresses

It is very unlikely that dynamic and static forces will act simultaneously. Shocks and impacts are the results of dry snowslides which take place during storms in midwinter. Although this is the time of greatest snow depth, the static pressures against structures -- called the "first type of loading" (fig. 17) -- are small.

Larger snow-pressure forces -- called the "second type of loading" (fig. 17) -- develop later when the snowpack, soaked with melt water, is settling rapidly. This is also the time of rapid glide motion.

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[9] *Frutiger, Hans. Lawinenverbauung "Mattstock"/Amden SG; Winterbeobachtungen 1959/60. Int. Bericht 351, 31 Oktober 1960. Eidg. Inst. für Schnee- und Lawinenforschung, Weissfluhjoch/Davos, Switzerland. [The "Mattstock" avalanche control project near Amden, SG; winter observations, 1959-60. Unpublished report 351, Swiss Fed. Inst. for Snow and Avalanche Res.]*

[10] *Frutiger, Hans. Lawinenverbauung "Mattstock"/Amden SG; Winterbeobachtungen 1960/61. Int. Bericht 394, 2 Oktober 1961. Eidg. Inst. für Schnee- und Lawinenforschung, Weissfluhjoch/Davos, Switzerland. [The "Mattstock" avalanche control project near Amden, SG; winter observations, 1960-61. Unpublished report 394, Swiss Fed. Inst. for Snow and Avalanche Res.]*

[11] *Frutiger, Hans. Lawinenverbauung "Kühnihorn"/St. Antönien-Castels; Winterbeobachtungen 1960/61. Int. Bericht 392, September 1961. Eidg. Inst. für Schnee- und Lawinenforschung, Weissfluhjoch/Davos, Switzerland. [The "Kühnihorn" avalanche control project near St. Antönien-Castels; winter observations, 1960-61. Unpublished report 392, Swiss Fed. Inst. for Snow and Avalanche Res.]*

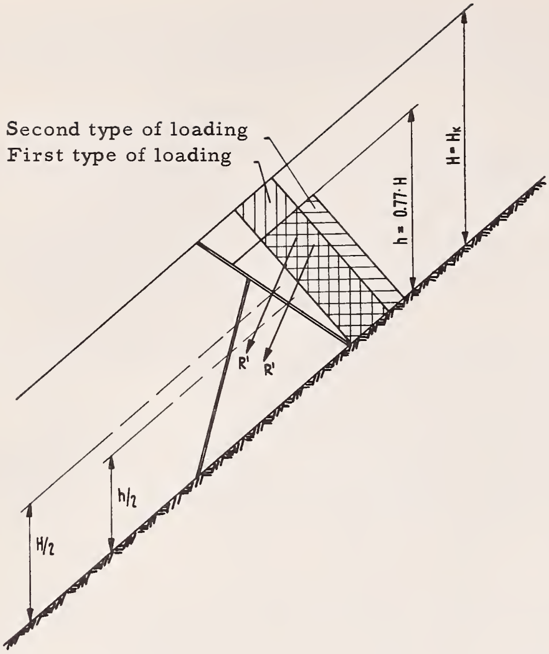


Figure 17.--Point of application of the resultant snow pressure force and distribution of the specific snow pressure for both types of loading.

These two aspects of the forces acting upon a supporting structure were described by de Quervain and Figilister (1953) as follows:

> As a rule the purpose of preventing avalanches is prevalent in midwinter when the snow depths, especially the new snow depths, reach their maximum. At that time snow-pressure forces normally are small because of the low density and low viscosity of the snow and because there is no glide all that time. In the period of high pressure (April, May, June, depending on the site), however, the occurrence of avalanches is less likely; the problem is to bring the structures through this period without damage.

2.4 Other Classes of Control Structures

It is not always economical and sometimes not even possible to install supporting structures in the starting zone. If the starting zone is too large, rugged, or remote in relation to the importance of the object to be protected, it is better to try other control possibilities in the lower parts of the avalanche area. These other classes of control structures, discussed below, were briefly referred to in the Guidelines (Art. 5).

2.41 Snowdrift Control

Structures to regulate drifting snow have a special place among avalanche control structures (Hopf and Bernard 1963). Normally, they are used in combination with supporting structures (figs. 18-20). In the Rocky Mountains, it is likely that modification of snowdrift patterns will become an essential part of any avalanche control measures in the starting zones.

The snowpack in the higher mountains, especially above timberline, will never be uniform. Wind action greatly modifies the snow deposition pattern, creating deep snow accumulations that make the control of many starting zones a real problem.

Figure 18.--Snow fences (upper right) on a flat ridge to catch drifting snow before it goes over the steep rim where it might become an avalanche. Clünas, Ftan, Switzerland. October 9, 1963.

Figure 19.--Jet roof (below) on a ridge to prevent a cornice. Clünas, Ftan, Switzerland. March 24, 1959.

Figure 20.--Wind baffles (lower right) on a ridge to prevent a cornice which menaces the supporting structures below. Kühnihorn, St. Antönien-Castels, Switzerland. January 15, 1958.

Two shapes of drifts are of special interest: the cornice and the roll. Only a few catchment basins can be found that do not have one or the other of these snow accumulation patterns (see fig. 27). Cornices and rolls steepen the snow surface, and their scarps are favorite starting spots for avalanches. Moreover, structures buried in deep accumulations are severely damaged by the settlement and creep of the snowpack in spring and early summer.

Snow fences, jet roofs (Düsendach), and wind baffles (Kolktafeln) are common types of drift structures. Snow fences (fig. 18) are used to catch drifting snow before it gets to spots where it would be troublesome. Jet roofs (fig. 19) are used to increase windspeed over the leeward edge of ridges where cornices and rolls tend to develop. Wind baffles (fig. 20) are used to create irregularities in the snow cover. The wind action around the baffles causes large wind scoops near the baffles and depositions in their lee. This is thought to prevent the buildup of excessive stresses within the snowpack. Wind baffles set in a line bordering the open flank of a structural control area are used to prevent a slab avalanche from spreading into the control area from neighboring, uncontrolled slopes (see Guidelines, fig. 10.2).

2.42 Guiding and Diversion Structures

Guiding and diversion structures may be useful in special cases, although they are generally of less importance than the other classes of control structures discussed in this Manual. They are constructed in or near the avalanche track, and are massive enough to withstand the impact of avalanches moving at full speed. The common types are the dam and the wall built of earth, stones, masonry, or concrete. A few diversion or guiding structures have been made from timber or steel, but it is usually not economical to use such materials since the structures have to be heavy enough to withstand impact loading.

Dams and walls may be built to keep the avalanche in its usual track or to divert it slightly out of its natural course. Depending on which function the structure is supposed to perform, they are called guiding structures or diversion structures. Guiding structures are useful to control sections of the track where curves or other natural obstacles may tend to divert the avalanche out of its usual path. The control works on Rogers Pass on the Trans-Canada Highway (Schaerer 1962b) include two guide walls to make sure the avalanche goes over an avalanche shed protecting the highway. In this way, the length of the shed was reduced. In Switzerland, some villages situated very close to avalanche tracks are protected by guide walls.

Diversion dams turn an avalanche away from an object to be protected. Diverting avalanches is a precarious and risky matter; too little is known about the behavior of avalanches encountering such structures to predict their effectiveness. If the angle of diversion is small, the terrain uniform and not very steep, and if enough material is available to build a high dam, it might be possible to control even dry-snow avalanches. Such structures are most effective, however, against wet-snow avalanches.

Diversion structures may also be considered a part of the group of retarding and catching structures that are used in the runout zone.

2.43 Retarding and Catching Structures

This type of structure, which stops the avalanche before it reaches the object to be protected, is effective only where the avalanche slows down naturally in a broad, flat section of the track or on a long, gently sloping runout zone. The most common types of retarding structures are mounds built of earth or stone, and fenders or bumpers usually built of concrete. Catching dams should be used in combination with a pit whenever possible. The control project on the Arzler Alm Avalanche near Innsbruck, Austria, is a fine example of how all of the above types can be used. Mounds are used in the runout zones of several avalanches on Rogers Pass in Canada (Schaerer 1962b). It must be emphasized, however, that there are only a few runout zones where such structures can be installed. Much of their effectiveness is lost if they are

installed at unfavorable sites. Schwarz (1960) and Roch (1964) say slopes should be less than 20° for retarding and catching structures to be effective. The problem can be best illustrated with four avalanche areas from the Colorado mountains (fig. 21):

	Stanley	Bethel	East Guadalupe	Battleship
Area of catchment basin (acres)	20	25	150	45
Average slope (percent):				
Whole track	50	52	45	45
Starting zone	60	70	76	63
Runout zone	32	40	20	32

The Stanley Avalanche (see fig. 27) has a small starting zone that is not too steep, a track that is regular and of medium steepness, and a runout zone above the lower loop of the highway that is about 1,000 feet (300 m.) long with an average slope of 32 percent. The runout zone is too short and too steep for retarding or catching structures. Moreover, the highway crosses the track again at a higher elevation. On the other hand, it would not be difficult

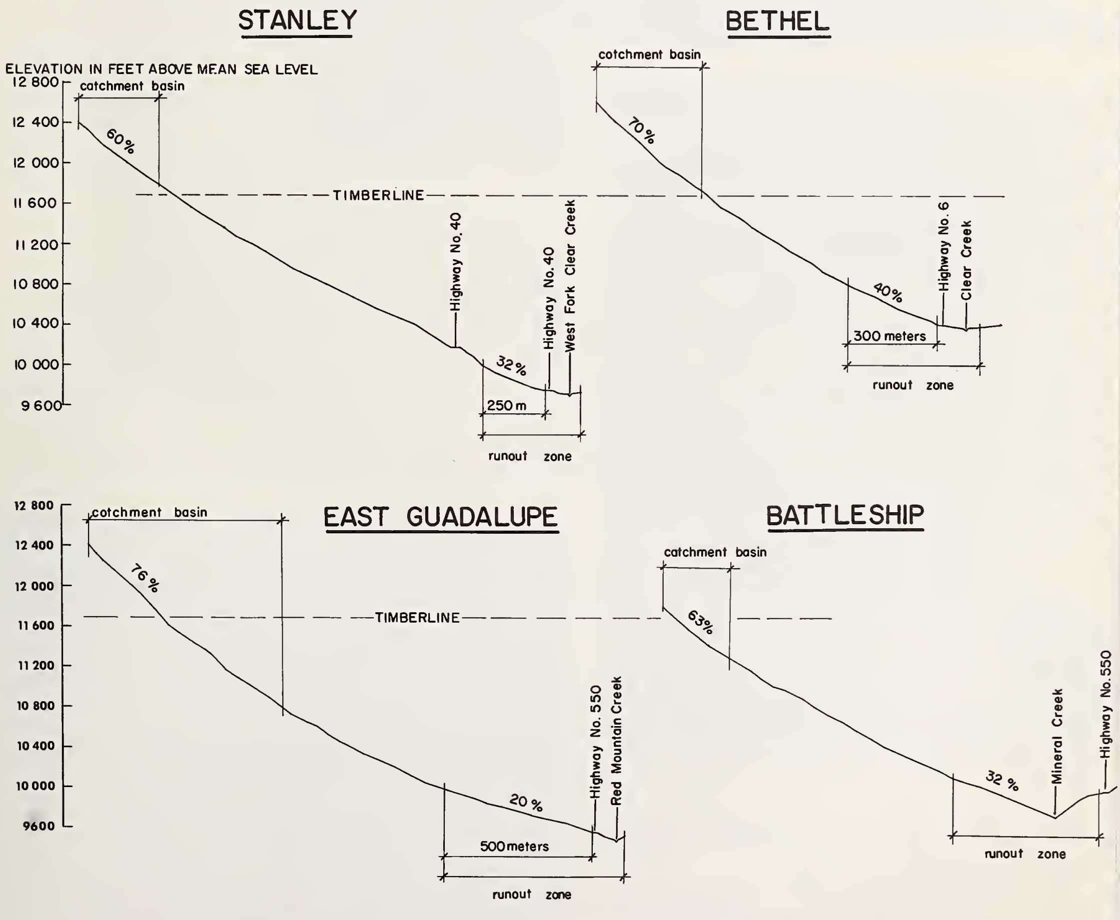


Figure 21.--Longitudinal profiles of four avalanche tracks. The examples used are the Stanley, Bethel, East Guadalupe, and Battleship Avalanches (see fig. 8).

to install supporting structures in the starting zone. Supporting structures in the starting zone and drift-control structures, then, would be the best type of control for the Stanley Avalanche.

In contrast, the East Guadalupe Avalanche along Highway 550 north of Red Mountain Pass has an extremely large, steep starting zone with cliffs exceeding 120 percent. The catchment basin of about 150 acres (60 ha.) has an average slope of 76 percent. The track is long, with an average slope of only 45 percent; the runout zone above the highway is long (1,600 feet; 500 m.) and gentle (20 percent). The large size and steepness of the starting zone makes supporting structures impractical. The length and gentle gradient of the runout zone, however, provide the features needed for successful retarding and catching structures.

The two earthen dams in the runout zone of the Bethel Avalanche[12] along Highway 6 west of Silver Plume, Colorado, should be mentioned here. These structures were built in the upper part of the runout zone, and were alined so that the upper one tends to divert the snow while the lower one acts as a catching structure. Although the dams do divert and catch large amounts of snow that would normally be deposited on the highway, the runout zone above them is too short and too steep (40 percent) for this type of structure to be highly effective. Should this avalanche run twice the same winter, the second avalanche probably would overrun the barriers because the snow from the first slide would greatly reduce their effectiveness.

In general, retarding and catching structures are useful where control of the starting zone would be too expensive, and where the avalanche runs too seldom to justify building an expensive avalanche shed. But they can give full protection only in very favorable terrain configurations. Normally, the effectiveness of retarding and catching structures is restricted to the reduction of snow removal.

2.44 Direct-Protection Structures

In some cases the terrain is so difficult and avalanches so frequent that the most economic solution to the problem is to protect the object directly. Direct-protection structures are not intended to retain, stop, divert, or slow down the avalanche; their only function is to directly protect the object. The most common type of direct-protection structure is the avalanche shed over highways and railroads (fig. 22). If the highway is put in a tunnel to avoid crossing an avalanche track, the tunnel would be another example of direct protection. In cases where the transmission lines have to cross avalanche tracks, the towers are sometimes protected by concrete walls built in the shape of a ship's prow (fig. 23). Other examples of direct-protection structures are earthen ramps or very strong walls and sheds on the uphill side of houses, built in the avalanche areas (fig. 24).

These structures give full protection, but they are very expensive. In addition, they do nothing to keep the avalanche from running and continuing to damage the forest and land. In Switzerland, they are used only when supporting structures or other types of structures cannot be used.

Direct-protection structures have to withstand the full force of a running avalanche. It is well known that avalanche forces are very great, but just how great is still unknown. Some years ago, the Swiss Institute for Snow and Avalanche Research started a program for the study of avalanche forces on an artificial avalanche track, the "Lawinengleitbahn" near Davos, and in the tracks of several natural avalanches (Roch 1962). Suggestions for the calculation of avalanche forces for different types of avalanches and for the design of avalanche sheds are given by Salm and Sommerhalder (1964), Schaerer (1965), and Voellmy (1955).

[12] *Stillman, R. M. The Bethel Mountain avalanche diversion barrier, U. S. Highway 6, Loveland Pass, Colorado. 1961. Alta Avalanche Study Center Project G, Report No. 1, 4 pp., illus. Wasatch National Forest, U. S. Forest Service, Salt Lake City, Utah.*

Figure 22.--An avalanche shed over U. S. Highway 160 near Wolf Creek Pass, Colorado. Two avalanche paths cross the three-lane highway at this point. December 1, 1965.

Figure 23.--Heavy concrete pillars used as fenders or bumpers to protect the towers of a power line. Ardüs, Davos, Switzerland. May 6, 1963.

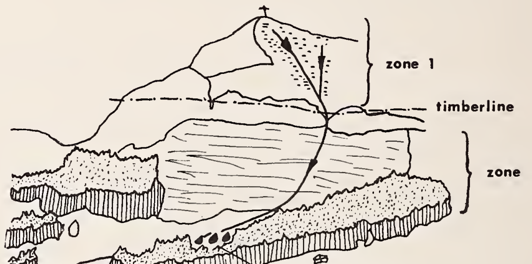
Figure 24.--Every house of the alpine settlement of St. Antönien has a mound of earth on the uphill side to protect it from avalanches. Gädmen-Matten-Meierhof, St. Antönien, Switzerland. July 30, 1963.

2.45 Combination of Several Classes of Control Structures

It is useful to combine, where possible, several classes of control structures on a single project. The control project on the Mattstock Avalanche near Amden, Switzerland, for example, uses four classes of control structures to protect the village (fig. 25). Permanent supporting structures (snow bridges and snow nets) and drift structures (wind baffles) were installed in the starting zone above timberline (fig. 25, zone 1). Trees were planted in the lower catchment basin since it is below timberline. Wide, earthen terraces were constructed to protect the young trees from excessive creep and glide of the snowpack, and to facilitate access to the plantation (fig. 25, zone 2). On a more gentle slope below the lower catchment basin, some retarding structures were installed. These earthen mounds (fig. 25, zone 3) are on pasture land where trees would be undesirable.

It is hoped that this combination of protective measures will give full protection to the village below. Moreover, there are other benefits: the pastures will no longer suffer from rockfall since they will be protected by the afforestation; the young trees will become a productive forest that renders more benefits to the owner than heavily used pasture land; and, the system of access roads built to bring in materials for the control structures will also be very useful for the management of the summer pastures.

Figure 25.--The Mattstock Avalanche control project, near Amden, Switzerland, uses four classes of control structures to protect the village.



2.5 Avalanche Control by Means Other than Structures

In the United States, most avalanche control work involves the use of explosives in one form or another (LaChapelle 1960). Where there is easy access to the top of the avalanche paths, such as in ski areas, hand-placed charges are often used. A man on skiis or in a chair lift can toss a charge of high explosives on to the slope near the expected fracture line with accuracy and comparative safety. Where winter access is dangerous or very difficult, explosives may be placed in the starting zone during the autumn. These are wired to a safe spot so they can be detonated electrically when avalanche danger is high. Normally, two, three, or more series of explosives are put out so several avalanche cycles can be controlled each winter. The use of preplanted charges is probably more common in Europe than in the United States (Schild 1957).

Artillery is also used to control avalanches on inaccessible slopes. In western United States, 75 mm. pack howitzers and 75 mm. or 105 mm. recoilless rifles are commonly used for avalanche control along the highways and on ski slopes (U.S. Forest Service 1961). These guns have a long range (7,000 yards; 6,400 m.) and good accuracy. The surplus military ammunition produces shrapnel, however, so care must be taken to avoid damage to the cables or towers of ski lifts as well as other structures near the impact area.

Zone 1: (above) Starting zone (catchment basin) is controlled by different types of supporting structures (snow nets and bridges) and some drift structures (wind snow baffles). Different depths to which structures are buried indicate variability of snow depths in area.

Zone 2: (upper right) Steep slope below timberline will be afforested. Lines of earthen terraces will protect young trees by reducing the glide of snowpack. In right middle ground, six earthen mounds (retarding structures) have been erected on a gentle transition slope in the avalanche track.

Zone 3: (right) On a gentle section of avalanche track, used for pasture, earthen mounds (retarding structures) 5 m. (16.5 ft.) tall and 40 m. (130 ft.) in circumference at base have been constructed. In left middle ground, a backfill (fender) on the uphill side protects a stable.

A recently developed compressed-gas gun, called the Avalauncher (U.S. ForestService 1964), which is now being tested, is lightweight, quiet, moderately accurate, and commercially available. Small cans of explosives are used as a projectile, with compressed inert gas as a propellant. The Avalauncher has a range of about 1,400 yards (1,300 m.) when a 12-foot barrel is used.

In Switzerland, explosives are used for avalanche control mostly on ski slopes where structures would interfere with ski activity. In such cases, the highly mobile, 8.1 cm. military mortar is used in preference to howitzers or recoilless rifles. In some other European countries, there are legal complications to the use of explosives for avalanche control.

In some cases, earthmoving equipment can be used to straighten and deepen the lower track or runout zone of an avalanche. This technique is most useful against wet-snow avalanches in areas where the objects to be protected are along the sides of the lower sections of the path. It would be less useful in areas of frequent, fast-moving, dry-snow avalanches.

Electrical and electronic devices have been used along highways and railroads to give warnings that avalanches have run (Hasler 1954, LaChapelle 1960, Schaerer 1962b). A detector is placed in the starting zone or the upper portion of the track. When this detector is disturbed, a signal along the road or railroad is activated, and traffic can be stopped before it reaches the avalanche zone.

Protective skiing is used to control small avalanches on or near many ski resorts. The mechanical action of the skis will often stabilize a new snow cover before avalanche hazard builds up. When snow accumulates on these slopes during periods of little or no ski use, it is sometimes possible to either stabilize the snow in place or to release unstable snow by skiing across the upper parts of the avalanche track (U.S. Forest Service 1961).

An elaborate avalanche-hazard warning service is provided the press and radio in the Alps and, to a lesser extent, in parts of Western United States and Canada. These bulletins describe existing snow conditions and give short-term forecasts of expected avalanche activity (Schild 1955, Wechsberg 1958). Although such warnings do not constitute avalanche control, they do help minimize the danger and inconvenience caused by avalanches.

3. The Role of Forests in Avalanche Control

A healthy, dense stand of trees is generally considered the best protection against avalanches. Just how trees stabilize the snow on steep slopes is not known, but it is a common observation that denuded slopes have more frequent avalanches than adjacent heavily forested ones.

Even a dense forest, however, cannot resist the tremendous force of large snow masses already in motion. Hence, to control avalanches that start above timberline, structures must be installed above timberline as well as in the area to be reforested.

Afforestations in avalanche areas that are entirely below timberline also need the help of structures to prevent the snowpack from gliding and pulling out the young trees before they are tall enough and vigorous enough to resist the snow-pressure forces. In avalanche tracks where trees are to be planted, the structures below timberline eventually will be replaced by the trees, but those above timberline must be considered permanent. Avalanche paths that have been created by careless timber cutting or burning offer the best chance for successful reforestation. The objection that trees at and near timberline grow too slowly to justify planting is not a valid argument. In fact, the slow growth rate is a strong argument for starting the job as soon as possible.

It is interesting to note that early avalanche control projects in Switzerland were established to protect existing forests and to permit reforestation of devastated areas. All Swiss avalanche control projects include the restoration of protective vegetation.

PART II.

BASIC CONSIDERATIONS IN PLANNING AN AVALANCHE CONTROL PROJECT

4. Observations and Surveys of the Avalanche Area

4.1 Snow Conditions

No avalanche control project should be started until a careful study has been made of the winter conditions in the project area. General information about winter conditions for the entire region as well as specific observations for the project site are important.

Usually it is not possible to get long-term observations for a particular control area. It is sometimes possible, however, to use long-term observations gathered at a study plot in the neighborhood to interpret the short-term spot observations taken at the project site. The more training and experience the interpreter has had, the better he will be able to extrapolate the general data to the project site.

Winter observations at the project site should extend over several years -- the longer the period the better. The following are among the more obvious questions that need to be answered:

> What is the maximum rate of snowfall for a given region?
> What are the general snow depths on the ground? What are the extremes?
> What are the average extreme snow depths for a control area?
> What are the wind patterns?
> What are the deposition patterns? How are the snow depths distributed?
> How does the wind influence the snow deposition?
> Are there possibilities of controlling snow deposition by drift structures?
> Where do the fracture lines of slab avalanches lie?
> Where are the starting spots of loose-snow avalanches? How often and how big do avalanches start?
> What would be the highest snow density?
> How much creep and glide is there in the snowpack?
> How long does the snow cover last?

Some people have the feeling that the starting zone of an avalanche is inaccessible in wintertime. That is not true. Extreme avalanche danger exists for only days or even hours. Between avalanche cycles there are long intervals when the experienced observer can penetrate the area without hazard. In the case of very remote, steep, or inaccessible spots, snow stakes can be used to permit reading snow depths from a distance with field glasses. The only difficulty is that the stakes usually disappear with the first avalanche.

For a given basin, the deposition patterns of the snow are rather constant from winter to winter. The cornices and rolls build up each winter at the same spots. An uncommon wind during a single storm, however, may temporarily change the usual pattern. Observations should extend over several years to be sure to include these unusual cases.

Snow settlement, creep, and glide measurements are important since they influence the load the structure must withstand. These data should be measured at the project site by one of several techniques. One technique requires a pit to the ground. Ping-pong balls are then placed in the walls of the pit at measured intervals in a vertical array above a marked point. The pit is back-filled with snow and left. Later in the spring the pit is dug again and the position of the balls is measured. Since creep and glide are most active in the spring, the pit must be dug at the time of maximum snow depth. In many areas this can be very laborious. Another technique involves the use of sawdust columns. At the time of maximum snow depth, a vertical hole is drilled through

the snow cover with a ram penetrometer, or a snow tube. A pointed wooden marker is dropped into the hole and driven into the ground to mark the spot. The hole is filled with sawdust. Later in the spring, after the snowpack has become isothermal and after the heavy spring settlement has taken place, the sawdust is exposed in a pit wall (see fig. 30), and creep and glide measured. Haefeli varied the second technique by using both ping-pong balls and sawdust (Bader et al. 1939).

Snow-density data should also be taken in any area where the density values or the altitude factor given in the Guidelines might not apply. The Federal snow sampler (Marr 1940) or 500 cm^3 cylinders (Bader 1962) are usually used to measure density.

4.2 Terrain Conditions

The cost of controlling avalanches with supporting structures depends primarily upon the extent and the terrain conditions in the starting zone. The form of the catchment basin and the kind of ground surface are factors that determine the spots likely to avalanche. As the terrain becomes more rugged, the prospects for successful control decrease. Slopes with cliffs are very difficult to control because loose-snow slides start in the cliffs. Starting zones below timberline can be controlled more economically than those above because of the possibility that an afforestation will eventually replace the structures. The accessibility of the area greatly influences transportation and labor costs. The surrounding terrain features also influence the type of transportation system (access road, cableway, or other methods).

Soil and rock conditions have to be explored thoroughly. Some decisions about the type of structure to be used can be made only after evaluating the soil and rock in the area. Nets, for example, can be used only if rock anchors can be placed in sound bedrock. If the ground is unstable (scree or talus), special foundations such as pressure bars have to be used. As a rule, bridges and rakes require bedrock within reach, which means the bedrock should not be deeper than 2 feet (1/2 m.). The quality of the bedrock has to be checked. If it is heavily fissured, it might be very difficult to drill the holes needed for the anchorage. Probe pits, and rock and soil tests (see Guidelines, appendix) give an estimate of subsurface conditions. Where structures have to be built on scree and detritus, the costs are appreciably higher than for those built on bedrock.

A survey of the area where structures are to be installed is recommended. It is preferable to have this survey done by the same engineer who will plan the structural control, because the field study forces him to make a thorough examination of the terrain conditions. The survey should answer the following questions:

> How big is the area to be controlled by structures?
> What are the exposure and the slope gradient?
> What are the possibilities and difficulties of access?
> What kind of soil and rock are present? Bedrock or scree?
> How deep is the detritus?
> Are there swamps or springs that may cause difficulties?

Much of these data are plotted on a large-scale map or a site plan of the area (see figs. 28, 29). The site plan also serves as a base for recording winter observations and for planning the arrangement of the structures. A scale of 1:500 to 1:2000 is needed, depending on the extent of the area and the kind of structural control.

5. Choice of Structure and Construction Materials

After the decision is reached that structural control is feasible for a given avalanche, the next decision concerns the type of structure. Where a high degree of protection from frequent, large avalanches is desired, either supporting structures in the starting zone or direct-protection structures are the logical choices. Which of these two types is a matter of comparative construction costs, with those costs governed primarily by the characteristics of the avalanche area.

Comparative costs for road or railroad protection in Switzerland (Frutiger and de Quervain 1964) have shown that 130 feet of avalanche shed costs the same as 1 acre of supporting structures (or 200 m. of shed per ha. of structures). Where a road or railroad crosses the same avalanche path more than once, or where an avalanche crosses a road on a wide front, supporting structures usually provide the highest degree of protection per dollar spent. For isolated buildings, high-tension transmission towers, and ski lift installations, direct-protection structures usually are the cheaper type of control.

Diverting and retarding structures or the use of explosives give satisfactory control in areas where less complete protection is acceptable and where avalanches are less frequent. This type structure is not effective on slopes steeper than 20 percent (see Sect. 2.4, p. 18; Roch 1964).

Supporting structures in the starting zone are the only type of structures that protect the avalanche track and the runout zone, as well as the only satisfactory system where reforestation is planned.

The type of supporting structure and the construction materials will depend on durability, exchangeability, maintenance, access, terrain features, and soils. Although not all factors can be discussed here, the most important properties of different types of supporting structures and building materials will be mentioned.

Any type of supporting structure -- open or massive -- should meet the following specifications:

> They should be at least as tall as the maximum snow depth expected under the worst conditions.
> There should be enough structures to control loose-snow avalanches.
> They must be strong enough to withstand dynamic and static pressures.

5.1 Open Supporting Structures

Although 80 to 90 percent of the structures in modern avalanche control areas are snow bridges, observations have indicated that snow rakes stop sluffs and resist snow pressures better (Roch and Sommerhalder 1961). Most avalanche control engineers consider the choice between rakes and bridges a matter of opinion, with cost the most important criteria. Either type requires a special pressure bar between the uphill and downhill footings in areas where bedrock cannot be reached (see fig. 15).

Snow nets (see figs. 13-15) should be used only in places where anchors can be placed in sound bedrock because the extreme tension forces on the guys require the best possible anchorage. Nets should not be used exclusively, however, for protecting large areas because the density of the supporting plane is not sufficient to prevent sluffs from flowing through and causing dangerous avalanches (Frutiger 1961).

Fences (see Sect. 10.1, p. 44, and fig. 31) may be useful in areas where extreme snow settlement is expected since the vertical configuration of these structures reduces the effect of settlement. On slopes, however, fences have less effective height than structures whose supporting grates are approximately normal to the slope.

5.2 Massive Structures -- Supporting and Direct-Protection

Massive supporting structures, such as walls, terraces, and dams made of earth, stone, or masonry, were once the prevailing structures used for avalanche control in the starting zone. Now they have been replaced almost entirely by open structures. For special purposes, however, they can still be very useful. If the slope to be protected is very steep or has cliffs in the upper portions, the topmost structures have to be strong enough to withstand falling chunks of snow and rock. In this case, massive structures are advantageous. Furthermore, massive structures are useful in deep snow accumulations where open structures are not strong enough to withstand the excessive snow-pressure forces. Here, a combination of a massive structure and an open one is recommended. For example, a steel fence mounted on top of a masonry or concrete wall gives a tall structure at modest costs, and is one solution for control of snow roll areas (see fig. 31).

No rigid design analysis is needed for most massive supporting structures. Normally, such types should be used only at sites where suitable rock for masonry can be found. Where suitable building material is absent, concrete could be used.

Of course, all structures subject to impact loading from moving avalanches have to be massive. This includes such structures as diversion dams, catching dams, and guiding and retarding structures. Avalanche sheds are the one type of massive structure that must be carefully designed to resist the dynamic forces of a moving avalanche (see Sect. 2.44, p. 22; Roch 1962, Voellmy 1955).

5.3 Construction Materials

Timber, steel, aluminum, concrete, and wire rope are used in the field of avalanche control engineering. Aluminum and prestressed concrete have been the most common materials. In recent years, however, there is a strong trend toward steel. The use of nylon is still experimental[13] (see Sect. 2.1, p. 9), and will not be discussed in detail in this Manual. Timber is still one of the most important building materials. It has been used from the very beginning of structural avalanche control, and is still the best for temporary supporting structures. Timber responds very well to snow pressure loads. It is strong, yet its great flexibility allows it to yield under heavy loads without permanent deformation. The main difficulty encountered with timber is its susceptibility to decay, which varies greatly with the species of wood and the climate of the site where it is used. Modern preservation methods (MacLean 1952), however, are highly effective in prolonging the useful life of most species of wood.

Experiences with steel in avalanche control areas in Europe show that corrosion under alpine conditions is slight and usually can be disregarded. In the United States, steel may become the most common building material for avalanche control. Where transportation is a problem, it might be more economical to use medium- to high-grade steel to reduce the weight.

Steel used in avalanche construction must be malleable enough to withstand the impacts of sluffs and slides during periods of low temperatures. This is particularly important for the grate, which is exposed directly to impact loading and to the very irregular forces of creep and glide. The framework is usually made from a high-grade steel with low to medium malleability.

Aluminum has been used in avalanche control work, primarily to reduce transportation costs in cases where such costs were disproportionately high. It was expected that the use of aluminum might be economical even though it costs about four times as much as steel per unit weight. Aluminum needs no protection against atmospheric influences. Unpainted aluminum structures are not desirable in areas where it is important to conserve the natural environment. Reflections of the sun or even of moonlight from the structures are visible for great distances.

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[13] *Frutiger, Hans. Rapport sur le voyage d'etude dans le Beaufortin (Savoie) pour faire connaissance des filets paravalanches en nylon. Int. Bericht 376, 19 Juni 1961. Eidg. Inst. für Schnee- und Lawinenforschung, Weissfluhjoch/Davos, Switzerland. [Report on a work trip into le Beaufortin Mountains (Savoy) to learn about nylon avalanche nets. Unpublished report 376, Swiss Fed. Inst. for Snow and Avalanche Res.]*

Some alloys of aluminum are subject to electrolytic corrosion if brought into contact with other metals (steel pins) and to chemical corrosion if embedded in concrete (footings). Therefore the properties of the alloy should be checked before it is used for avalanche control structures.

Concrete structures are very heavy, and special equipment is needed to assemble the structures at the erection site. A single beam weighs about a ton. Prestressed concrete members are subject to heavy transportation damage and therefore need very careful handling. The installed structures also need special protection if they are exposed to rockfall. Like aluminum, concrete structures need no protection against corrosion, and because of their weight damage by snow-pressure forces is not likely.

Wire-rope snow nets are the lightest structures in common use. A normal net 10 by 10 feet (3 by 3 m.) weighs about 66 pounds (30 kg.). The heaviest member is the steel-tube swivel post, which weighs 130 to 220 pounds (60-100 kg.). One or two men can backpack the whole snow net, and no special arrangements are needed for installation. The wire rope, made of galvanized steel wire, is made into snow nets, then coated with a green oil varnish, which not only protects it from corrosion but renders it quite inconspicuous.

6. Arrangement of Supporting Structures

The arrangement of supporting structures is based on an analysis of terrain and snow conditions. Since control projects must start at the top of the avalanche area and progress downslope, any numbering system for lines of structures or for individual structures should start at the top. The choice between continuous, interrupted, and staggered arrangement of structures is based mostly on the uniformity of the terrain and the type of structure used. Where there are numerous large rocks or knolls, a staggered arrangement is usually best. A continuous arrangement is easiest to use in uniform terrain, and is less subject to end effect forces. The interrupted and staggered arrangements have been used most often, but the trend now is toward a continuous arrangement because it gives better control of sluffs. Experience in Switzerland has also shown that when the heavy, prestressed concrete bridges (see fig. 12) are used, the continuous arrangement is more economical.

Individual structures should be built with their long axis perpendicular to the fall line at the structure site, whether an interrupted or a continuous arrangement is used. In an interrupted arrangement, the gap (interval) between adjacent structures built on the same contour line should be no more than 6 feet (2 m.). If adjacent structures are uphill or downhill from each other, the projection of the horizontal distance (interval) between the structures decreases the farther they are apart. When the slope distance between structures reaches 20 feet (6 m.), the interval finally reaches zero (see Guidelines, Art. 23).

When local areas of exceptionally deep snow, such as cornices and gullies, are encountered in an avalanche control area, special structures or arrangements may be needed (see Sect. 10.1, p. 44). In some cases snow fences or other types of drift structures may be helpful in controlling snow depths. The ultimate solution will usually vary from project to project.

Recent experience in Europe has shown slope distance between structures and width of the opening between members of the grate (as given in Guidelines, Art. 21, 58) are too great for complete protection. To prevent <u>all</u> avalanches, slope distance and width of opening should be reduced to half of that recommended in the two Articles, and a continuous arrangement should be used. Because the increased number of structures would increase costs considerably, it is necessary to decide very early in the planning stage what degree of protection is needed on each avalanche control project. It is often possible to get 80 to 90 percent protection for about half the cost of complete protection.

To help decide the necessary degree of protection, each avalanche area can be observed according to the following avalanche-hazard classification:

> Class 1. Frequent avalanche hazard:
Avalanches run once to several times each winter.

> Class 2. Occasional avalanche hazard:
Avalanches occur once each 3 to 6 years. A heavy snowfall on a deep unstable snowpack is usually needed to cause avalanches.

> Class 3. Erratic avalanche hazard:
Avalanches run only under extreme weather conditions, which may not occur for decades -- unusually heavy snowfall or drifting on a highly unstable snowpack.

Along highways, areas in classes 1 and 2 usually require structures; areas in class 3 would not, since it is much cheaper to close the highway when extreme conditions develop than to try to stabilize the area. But if permanent settlements exist in a class 3 area, control is mandatory. Because complete protection is so expensive, avalanches may still occur under catastrophic conditions. Permanent dwellings should be prohibited in any recognizable avalanche-hazard area, regardless of its classification.

7. Design of New Structures

Although designs for structures to control avalanches will change as new materials and equipment become available and as engineers gain experience, the rules and suggestions developed to date will be useful to the engineers who are just entering the avalanche control field. Form, size, and type of structures cannot be standardized because of the variations in snow and terrain conditions, but design criteria essential to any structure are covered in this Manual and in the Guidelines.

The first step is for the avalanche control engineer to gather data on snow depths, snow movement, snow pressures, soil stability, terrain roughness, accessibility, and other pertinent information. From this, design engineers can determine the best size, shape, and type of materials to use, based on the most up-to-date techniques and practices.

The design criteria for supporting structures are usually computed for two types of loading (see fig. 17; also Guidelines, Art. 53). The first, typical of winter conditions when snow depths are great but snow density is low, is based on a maximum snow depth equal to the maximum height of the structure (H). Snow density for Swiss conditions is set at 0.270 t/m^3 (0.27 g/cm^3) for the reference elevation of 1,500 m. on a northerly aspect (see Guidelines, Art. 52). The resultant force is applied at the midpoint of the structure.

The second type of loading is typical of spring conditions after settlement has reduced snow depths and increased snow density. This type of loading is based on a snow depth only 77 percent of the maximum height of the structure (0.77 H). Snow density is increased to 0.400 t/m^3 (0.40 g/cm^3) for an elevation of 1,500 m. and a northerly aspect. The resultant force is applied at 0.385 times the maximum height of the structure (0.385H). In general, structures designed to withstand the heavy loading during spring months (second type of loading) will be strong enough for winter conditions.

Design criteria must also allow for several additional types of loading. One of these is the force created by snow flowing around the ends of structures. This end effect force must be computed for both the first and second types of loading. Another force to be considered is the side load that acts parallel to the contour lines or across the slope. This force acts uniformly over the structure and tends to create lateral instability. A third force which acts parallel to the supporting plane of the structure is called transverse loading. This force can act either up or down and tends to shear the bars of a snow bridge from the trestle.

Guler (1959) illustrates how the numerous forces act on the various parts of open, framed structures, and supplies the details of construction methods in current use.

For design purposes, snow density is adjusted from the reference altitude of 1,500 m. by an altitude factor, f_C. In Switzerland, this factor shows a 2-percent increase for each 100 m. between 1,500 and 3,000 m. (see tabulation, p. 16).

PART III.

THE STANLEY AVALANCHE CONTROL PROJECT -- A CASE STUDY

Part III combines field data on snow cover and terrain conditions with the information in the Guidelines and Parts I and II to develop an avalanche control plan for a specific area -- the Stanley Avalanche.

The Stanley Avalanche starts at 12,400 feet elevation m.s.l., in an alpine bowl about 2 air miles south of Berthoud Pass, Colorado (figs. 26, 27), and extends to Clear Creek, at 9,680 feet m.s.l. The track crosses both limbs of a switchback on U. S. Highway 40. The avalanche runs several times each winter, but does not always cross the highway in both places. Present avalanche control is by artillery fire, which either stabilizes the snow in place or causes it to avalanche.

Previous observations (see Sect. 2.43, p. 20) indicate the best control method would be to use supporting structures in the starting zone with drift-control structures to the windward of the catchment basin. Although an avalanche shed over one or both loops of the highway would be an alternative, the expense of two sheds would be prohibitive; a single shed over the upper road would leave the lower road unprotected because the runout zone is too steep and short for retarding and catching structures.

8. Winter Observations

8.1 Snow Depths

The design of an avalanche control project based on supporting structures requires data on snow depths, measured at the places where the structures are to be built. Field observations of the distribution of snow depths and creep-and-glide measurements were taken in the catchment basin of the Stanley Avalanche during the period of April-June 1962. Snow depths were measured along several profile lines (fig. 28) and were plotted on a map of the area (fig. 29). This type of map should also be used to report the exact location of the fracture lines of slab avalanches. This was not done for the Stanley Avalanche during the 1961-62 winter because detailed maps were not available until August 1962.

The roll of snow on the west rim of the catchment basin is of particular interest. Preliminary investigations revealed that snow depths there are too great to be controlled by normal types of structures. The deep accumulations on this east-facing slope contrast conspicuously with the west-facing one, which was swept bare by the winds all winter.

Two main problems were revealed by the snow conditions in this particular case:

> Can the excessive snow accumulated in the roll be stabilized?
> Does the south-facing slope also receive dangerous masses of snow under exceptional wind conditions?

Both problems should be studied carefully. It might be possible to use some type of snow-drift control together with exceptionally strong and high structures to stabilize the roll. Winter observations should be continued long enough to answer the second question.

Although snow depth and fracture line locations need to be recorded for several more winters to get a comprehensive estimate of winter conditions for the Stanley Avalanche, many years of weather data collected at nearby Berthoud Pass present a good picture of Rocky Mountain weather conditions (Judson 1965).

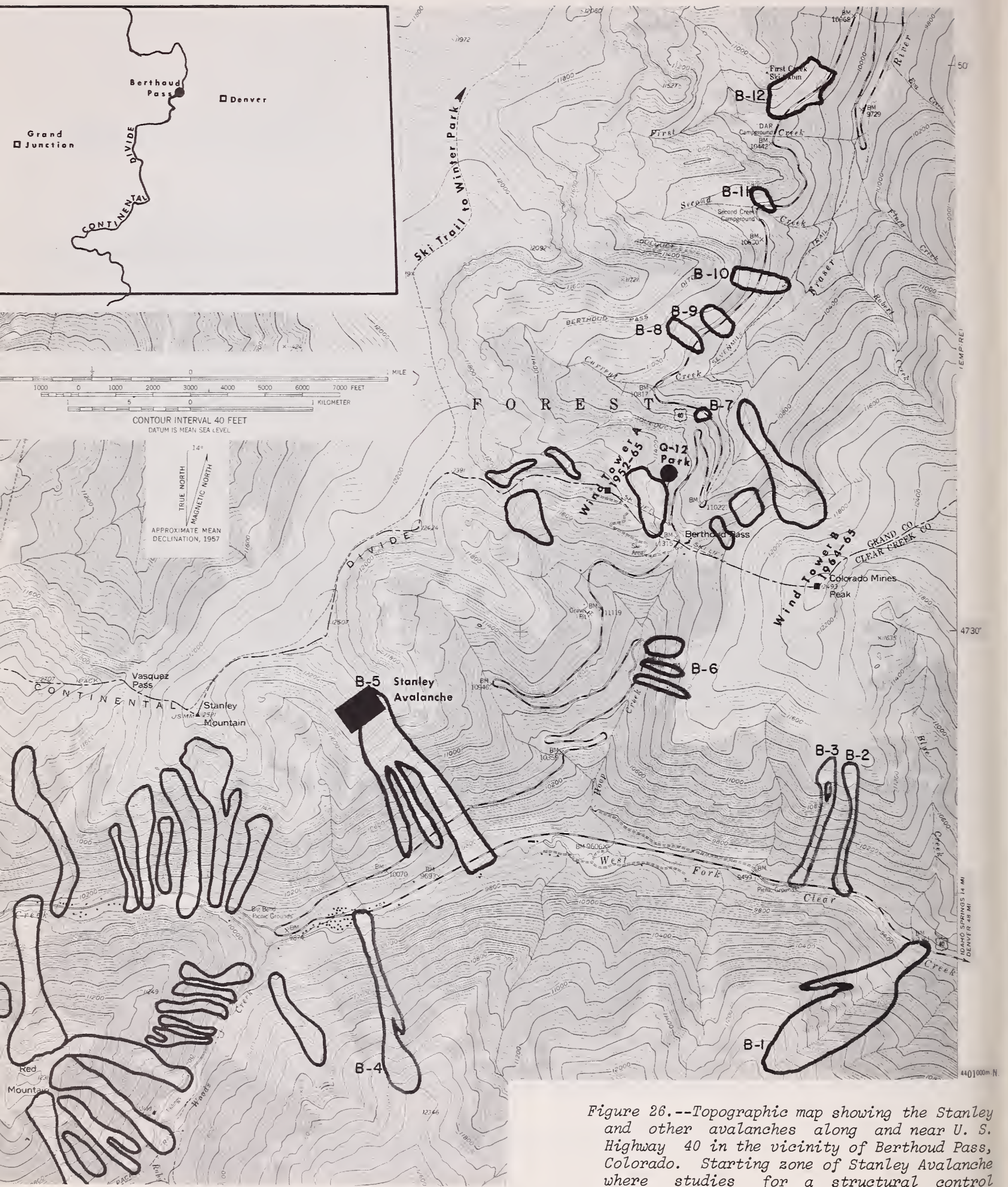


Figure 26.--Topographic map showing the Stanley and other avalanches along and near U. S. Highway 40 in the vicinity of Berthoud Pass, Colorado. Starting zone of Stanley Avalanche where studies for a structural control project were made is marked with a rectangle.

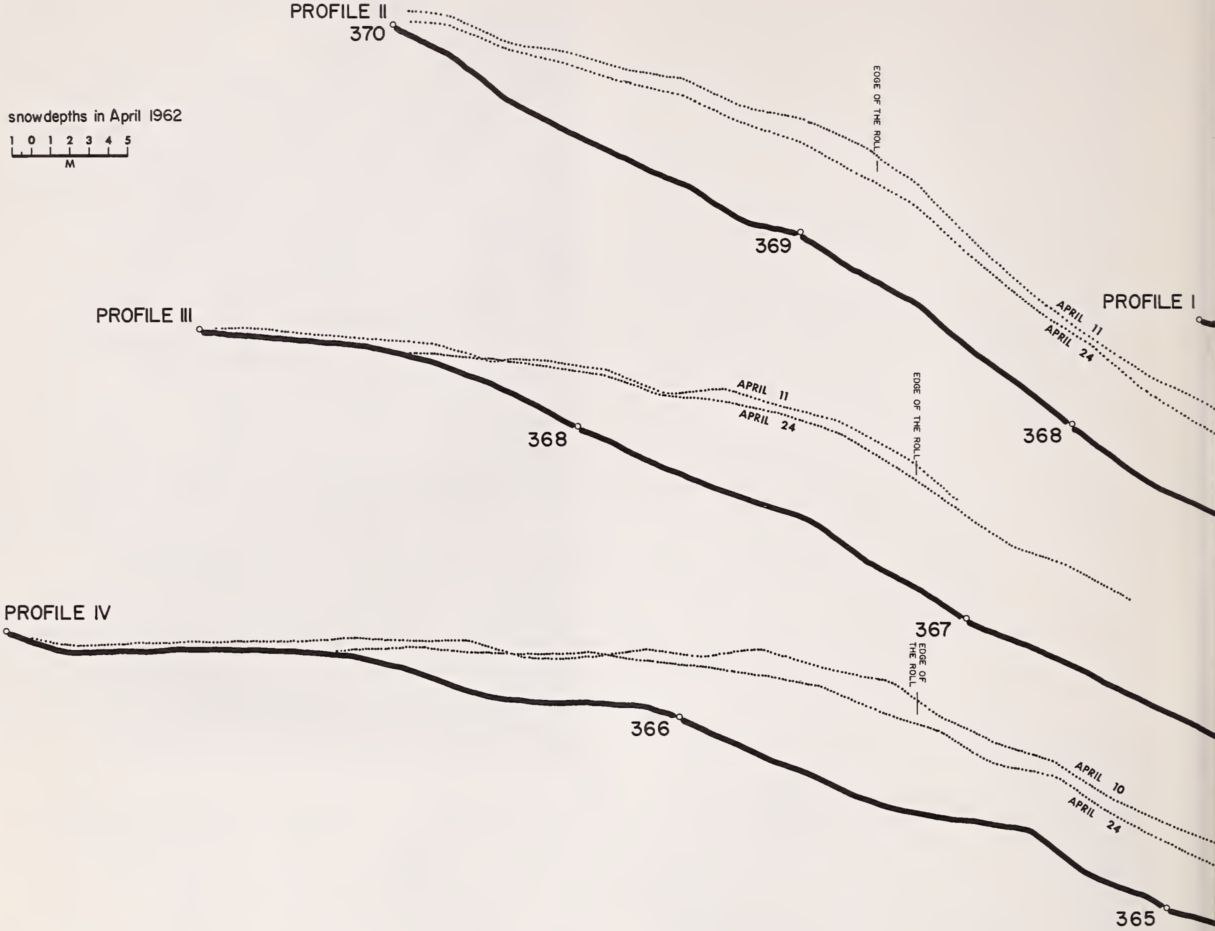
Figure 27.--The path of the Stanley Avalanche, Berthoud Pass, Colorado. This avalanche path crosses the highway in two places. The snow patch in the upper left is the remains of the deep snow roll formed by snow blown from the ridge into the catchment basin. June 18, 1962.

Permanent snow cover starts in late October or early November; snow depths increase linearly from November through February (table 1). Average snow depth by mid-February is 58 inches (1.5 m.). Precipitation increases during March, April, and May. Although maximum snow depth normally occurs April 10-15, it has been recorded as early as March 14 and as late as April 20. The greatest snow depth observed in 13 years of record at the Berthoud Pass study field -- a small opening in the forest one-fourth mile north of the Pass, called Q-12 Park -- was 115 inches (292 cm.) on April 21, 1951 (Judson 1965).

With rising insolation and higher temperatures, the snow cover begins to settle appreciably about the time of maximum snow depth. In this region, highest precipitation is during April and May. Snow depth does not decrease greatly until late May, when the snowpack begins to melt rapidly because of increased insolation and longer periods of clear weather. Rate of snowmelt during late May and early June is 19-20 inches (50 cm.) of snow per week (table 1).

In general, snow depths do not adversely affect structures. Even the extreme of April 1951 with 9 feet (2.7 m.) of snow on the ground is not alarming, because the same winter the extreme snow depth on the study field at Weissfluhjoch, Switzerland (8,000 feet m.s.l.) where there are many structures was 12 feet (3.6 m.). The big difficulty in Colorado is not heavy snowfall; it is the heavy wind transport that alters the deposition pattern of the snow and creates extreme snow depths in local areas.

In terms of structural engineering, any structures built on the Stanley Avalanche would serve the functional purpose of preventing slides for the 5-month period, November-March; they also would have to endure their heaviest loading during April-May when they would be subjected to the enormous pressures in the settling snowpack (see graph with table 1).


PROFILE II
370
369
368
PROFILE I
PROFILE III
368
367
PROFILE IV
366
365
snowdepths in April 1962
1 0 1 2 3 4 5
M
EDGE OF THE ROLL
APRIL 11
APRIL 24
APRIL 10

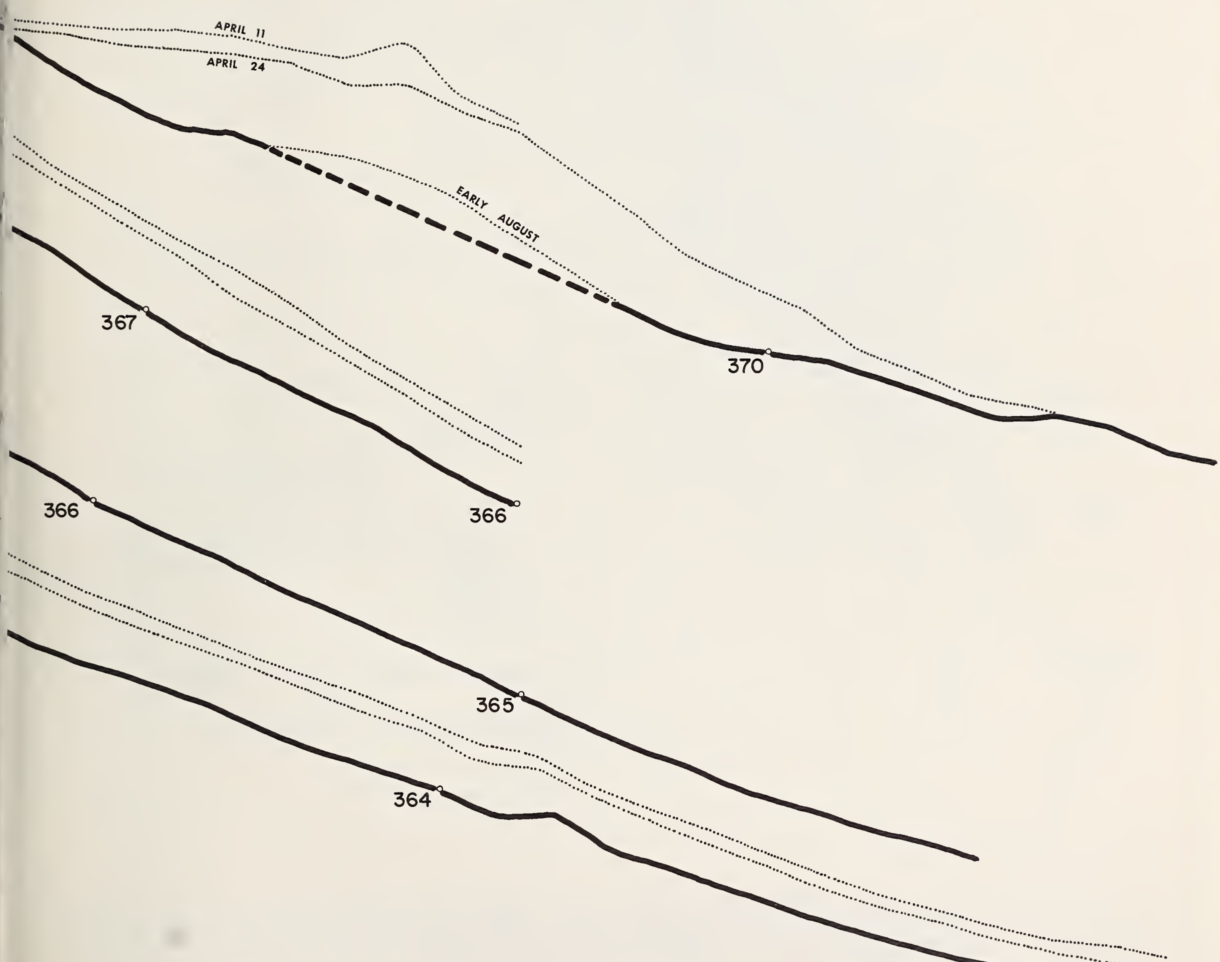


Figure 28.--Four profile lines across the starting zone of the Stanley Avalanche. Snow depths are for April 1962.

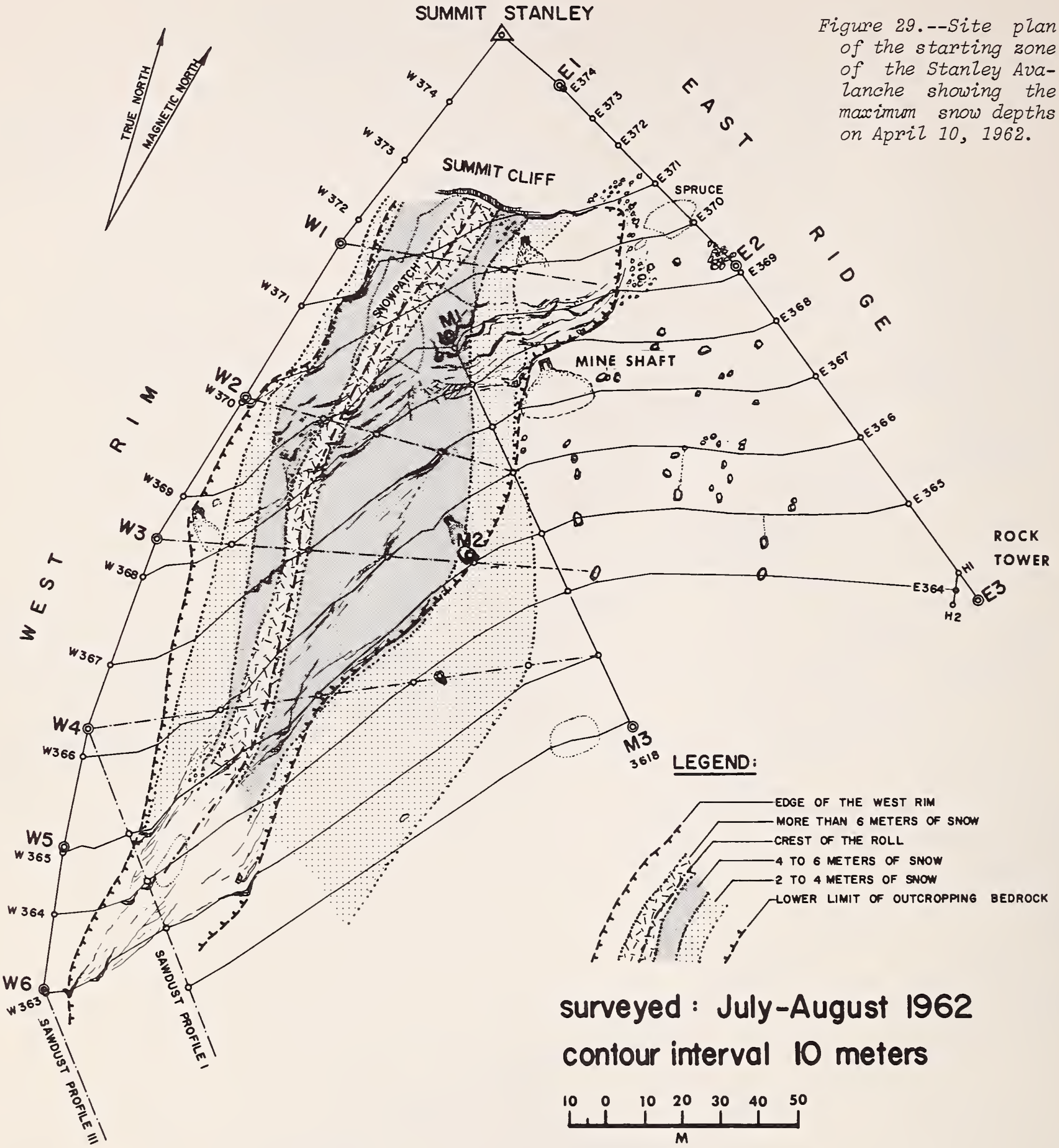


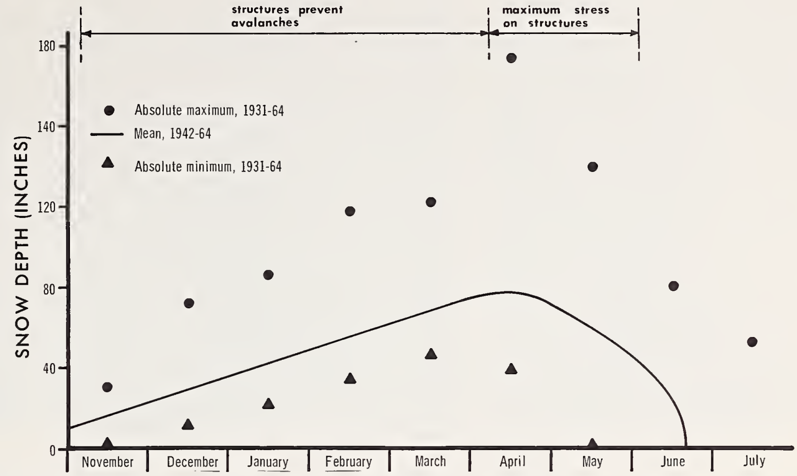
Figure 29.--Site plan of the starting zone of the Stanley Avalanche showing the maximum snow depths on April 10, 1962.

8.2 Creep and Glide

Glide of snow cover is assumed to be of much less significance in the Colorado Rocky Mountains than in the Swiss Alps, because conditions that favor gliding -- warm wet ground covered with long grass -- are not common in the Rockies. Creep is to be expected, however, and must be seriously considered when planning structures because creep due to intense snow settlement causes large pressures.

Some investigations of creep and glide were conducted during the winter of 1961-62 in the catchment basins of the Stanley and Bethel Avalanches in the Berthoud-Loveland Pass area.

Table 1. -- Snow depths[1] at Berthoud Pass, Colorado, taken from daily readings, November-April 1942-64. Graph illustrates depth of snowpack. Structures would prevent avalanches for 5 months (November-March), but would have to endure enormous pressures of settling snowpack (April-May).



Season	November				December				January				February				March				April			
	First	Fifteenth	Minimum	Maximum	First	Fifteenth	Minimum	Maximum	First	Fifteenth	Minimum	Maximum	First	Fifteenth	Minimum	Maximum	First	Fifteenth	Minimum	Maximum	First	Fifteenth	Minimum	Maximum
	Inches																							
1942-43	--	--	--	--	--	40	--	59	60	53	46	60	59	64	59	69	69	85	69	86	75	92	75	95
1943-44	--	11	5	25	23	24	22	34	38	30	30	43	43	54	43	56	56	55	55	68	68	76	64	94
1944-45	--	6	--	12	12	20	12	24	24	36	24	39	39	49	39	55	54	64	54	74	74	--	54	--
1945-46	10	17	10	26	25	36	26	56	55	54	53	60	55	70	55	75	74	67	65	76	64	66	--	--
1946-47	11	15	11	19	19	29	19	31	31	36	29	36	34	42	34	62	62	59	59	80	80	109	80	110
1947-48	16	11	16	30	30	30	30	34	38	42	38	62	59	57	55	66	66	72	66	84	80	74	68	94
1948-49	6	15	6	21	21	32	21	60	60	51	51	61	58	67	59	70	70	84	79	85	83	85	--	94
1949-50	12	14	4	14	10	14	8	22	16	25	16	43	44	48	43	57	56	58	52	74	77	72	64	82
1950-51	--	--	--	--	--	--	--	--	--	39	--	66	46	76	60	80	73	84	73	92	91	105	--	115
1951-52	--	--	--	24	22	35	22	72	69	55	55	74	70	72	69	87	75	79	75	94	95	90	75	101
1952-53	--	--	--	--	--	21	10	28	28	36	28	48	44	52	44	58	50	53	50	67	65	72	--	72
1953-54	--	--	--	--	--	31	21	38	31	32	29	37	34	35	32	44	44	47	43	60	56	41	--	56
1954-55	--	--	--	--	23	25	22	30	28	34	28	43	42	45	42	53	53	69	49	73	68	69	--	76
1955-56	--	26	--	28	24	30	24	48	37	47	33	64	59	72	56	74	65	70	63	70	63	79	--	83
1956-57	--	17	11	24	17	31	17	34	30	54	30	58	50	50	48	61	62	65	58	72	66	100	--	108
1957-58	6	18	6	24	23	29	22	46	41	39	36	55	54	63	51	71	62	75	61	86	82	85	80	95
1958-59	--	6	0	19	18	40	18	42	34	39	34	52	52	48	48	73	70	73	68	81	74	77	69	83
1959-60	--	27	--	36	34	33	32	40	38	50	38	54	48	66	48	73	74	93	74	93	87	67	58	87
1960-61	--	13	--	16	16	21	16	34	30	36	29	41	36	38	36	49	48	50	46	60	61	72	58	76
1961-62	21	29	21	33	40	35	33	44	56	63	46	64	67	67	59	77	--	77	67	79	88	88	61	90
1962-63	0	2	0	10	6	11	6	20	17	22	17	36	37	40	37	55	54	53	48	60	48	39	33	52
1963-64	6	5	4	10	8	17	8	31	25	28	23	32	30	37	30	47	44	52	43	67	60	69	59	72
Total	88	232	94	371	371	584	389	827	786	901	713	1128	1060	1212	1047	1412	1281	1484	1317	1681	1605	1627	898	1735
Mean	10	14	8	22	21	28	19	39	37	41	34	51	48	55	48	64	61	67	60	76	73	77	64	87

[1] Readings December 1942 to April 1951 taken at Bowl behind lodge; November 1951 to April 1964 at Q-12 Park.

Three series of four to six sawdust columns were installed under conditions conducive for maximum creep and glide -- steep slopes, southerly aspects, and deep snow (table 2; fig. 30). Methods used are described here to serve as examples for future studies.

A penetrometer was used to make holes in the snowpack. The lower end of the vertical hole was marked by a wooden peg, which was dropped down the hole and driven into the ground. Experience with the very dense snow in the deep accumulations revealed a need for a better hole-drilling technique. Ice layers within the snowpack very often gave trouble, and it was difficult to mark the

1/6 1/5 1/4

Figure 30.--Photographs show sawdust columns in the Bethel and Stanley Avalanche areas, spring 1962. Drawings show the sawdust profiles, winter 1961-62: A, creep and glide movement of snowpack; B, site plan; and C, longitudinal section of sawdust column series I.

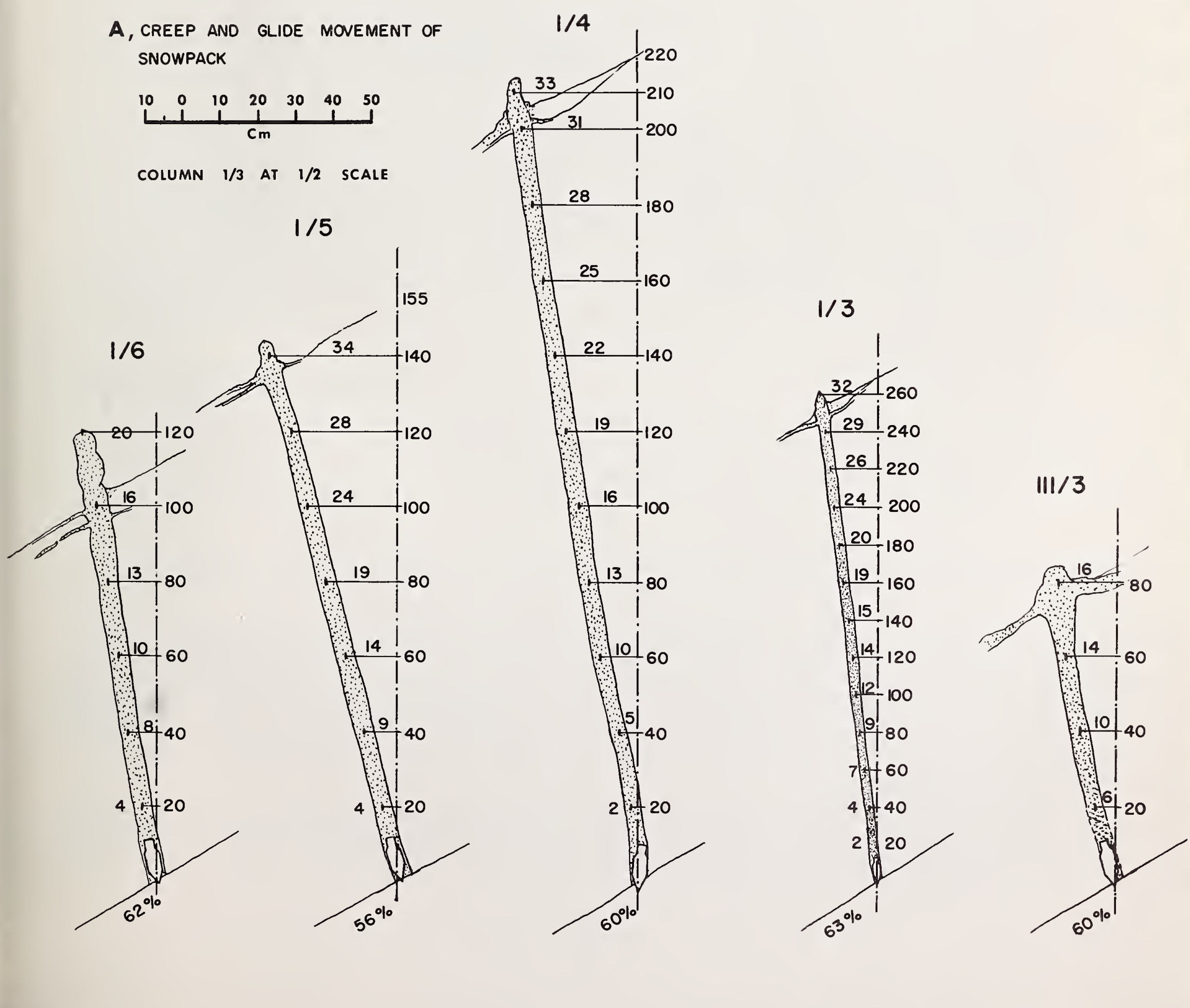
Table 2.--Three series of creep and glide tests, using sawdust columns, installed on southeast slopes at time of greatest snow depth, Stanley and Bethel Avalanches, Berthoud-Loveland Pass areas, Colorado, 1962

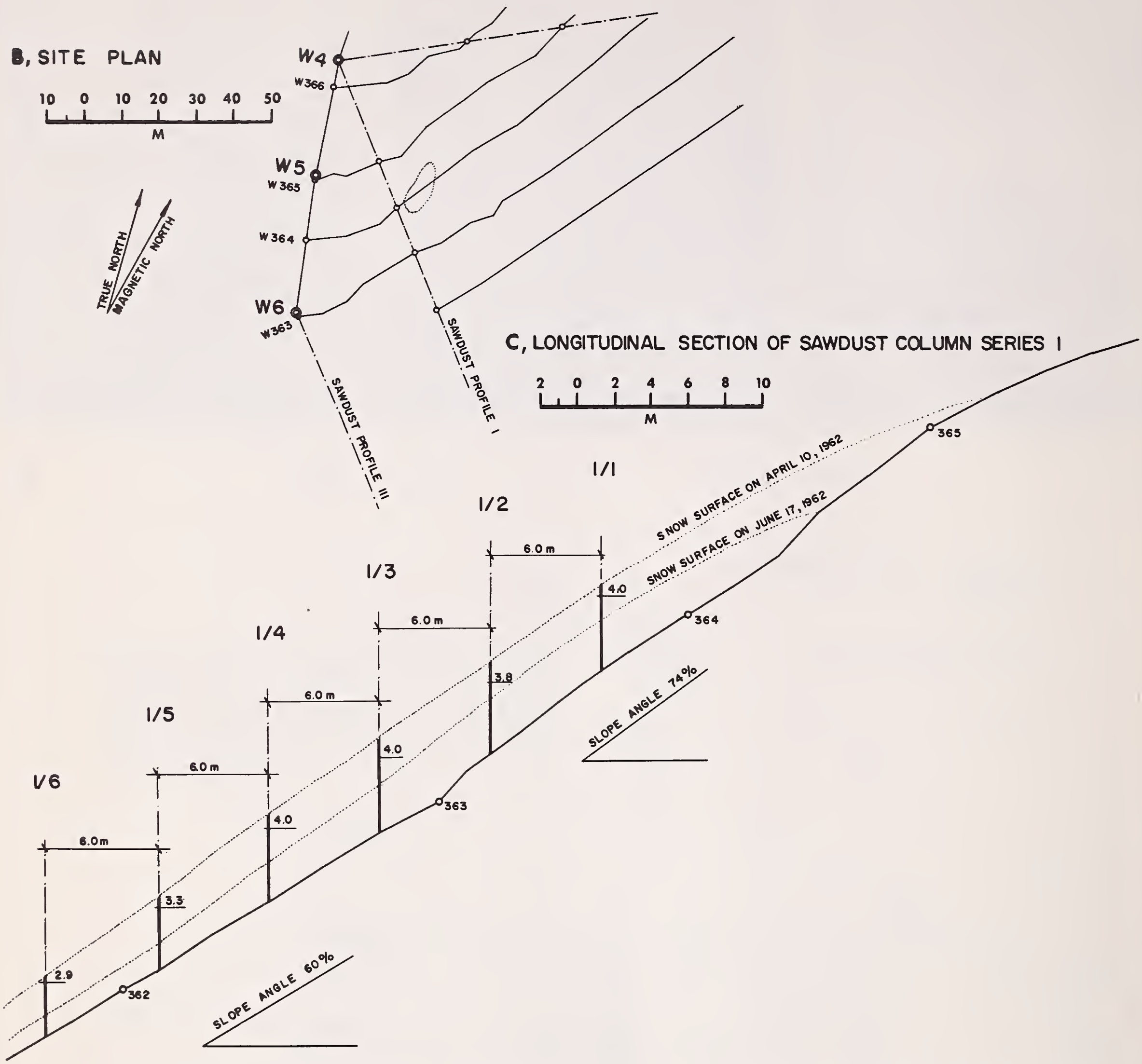
Series number, location, and ground-surface characteristics	Slope	Altitude	Columns	Distance between columns	Duration of test	Date of installation	Date pits opened	Data collected
	Percent	Ft.m.s.l.	No.	Feet	No. days			
I. Stanley Avalanche: west roll of catchment basin; rock detritus, fine and coarse material; very little vegetation--only scattered bunches of grass.	60-74	12,000 (3,640 m.u.m.)	6	19.5 (6 m.)	68	Apr. 10	June 17	Columns 3-6 opened; columns 1-2 still had snow depth over 10 feet (3 m.), but snow was melted when checked July 9.
II. Bethel Avalanche: cornice along west rim of catchment basin; outcropping bedrock and rock detritus, mostly coarse material; very little vegetation.	90	12,100 (3,700 m.u.m.)	6	13.0 (4 m.)	65	Apr. 12	June 16	All profiles melted off except column 2 where snow depth was only 26 inches (65 cm.).
III. Stanley Avalanche: same conditions as Series I.	60-74	12,000 (3,640 m.u.m.)	4	19.5 (6 m.)	76	Apr. 24	July 9	All profiles melted off except column 3.

I/3

III/3

II/2


A, CREEP AND GLIDE MOVEMENT OF SNOWPACK
10 0 10 20 30 40 50
Cm
COLUMN I/3 AT 1/2 SCALE
I/6
20 120
16 100
13 80
10 60
8 40
4 20
62%
I/5
155
34 140
28 120
24 100
19 80
14 60
9 40
4 20
56%
I/4
220
33 210
31 200
28 180
25 160
22 140
19 120
16 100
13 80
10 60
5 40
2 20
60%
I/3
32 260
29 240
26 220
24 200
20 180
19 160
15 140
14 120
12 100
9 80
7 60
4 40
2 20
63%
III/3
16 80
14 60
10 40
6 20
60%



lower end of the column because of rocks and boulders on the ground. Perhaps a modified snow sampler with a special cutter would solve the ice-layer problem.

Records were obtained from only 6 of the 16 columns because the others melted out faster than anticipated. The 6 profiles were so similar, however, that it can be assumed with great probability that the other 10 columns would have revealed nothing new. No gliding was found, and the creep showed the usual pattern known from other investigations (Bader et al. 1939, Martinelli 1960).[14] When structures are built in areas where deep snow accumulates, as would be the case in the Stanley and Bethel Avalanche areas, they must be constructed to withstand the large pressures created by snow creep.

[14] *Frutiger, Hans. Eine Winterbeobachtung in der Lawinenbauung "Clünas"/Ftan GR. Int. Bericht 383, 14 August 1961. Eidg. Inst. für Schnee- und Lawinenforschung, Weissfluhjoch/Davos, Switzerland. [A winter's observation in the "Clünas" avalanche control project, Ftan GR. Unpublished report 383, Swiss Fed. Inst. for Snow and Avalanche Res.]*

9. Terrain Analysis

The Stanley project area was surveyed in July and August 1962. The site plan (see fig. 29) made from this survey was used to plot snow depths, soil and bedrock conditions, fracture line location, and as a base map for the arrangement of supporting structures.

9.1 General Configuration

The catchment basin of the main part of the Stanley Avalanche is confined on both sides by ridges that are bare year-round because the snow is blown off by high winds. The two lateral profiles marked by survey points W1 to W6 and E1 to E3 follow these ridges. The upper limit of the area is the top of the mountain "Summit Stanley" with a spot elevation of 12,400 feet (3,750 m.) above m.s.l. The lower limit was chosen somewhat arbitrarily following approximately the contour line at 11,900 feet (3,620 m.) m.s.l. It must be emphasized that the catchment basin of the Stanley Avalanche extends to the west of the area shown on the site plan. Here two secondary tracks originate. In addition, there are steep slopes in the main track near timberline. Although not covered in this report, these secondary tracks and the steep slopes in the lower part of the main track also should be controlled.

The total area of the project shown on the site plan is 6.65 acres (2.69 ha.). This area can be subdivided into three distinct parts:

> The very steep and exposed summit cliff above the contour line at 12,200 feet (3,710 m.).
> The southeast slope, west of profile M1 - M3.
> The south slope, east of profile M1 - M3.

Normally there is only a little snow on the summit cliff because it is too steep and exposed. When planning the arrangement of the structures, however, care must be taken to control loose-snow slides and even small slabs that may start in this spot, which is too rugged and steep to be controlled directly. The starting spots of the main Stanley Avalanche lie on the southeast slope between 11,900 and 12,200 feet (3,620 and 3,720 m.) m.s.l. This starting zone covers an area of 4.55 acres (1.84 ha.). The south slope, which is less steep, is normally blown bare by high winds. Additional winter observations will be needed to see if this area has to be controlled for unusual snow deposition patterns.

9.2 Soil and Bedrock Conditions

Conditions are generally favorable for the foundation of the structures. There are two types of bedrock in the project area. The summit cliff is a big dyke of coarse, pinkish granite. There are several secondary veins of the same rock downslope. The remaining bedrock is a darker, fine-grained Pre-Cambrian gneiss or schist. Both types of rock would be good foundation material, but both have fissures that might give some difficulties for rock drilling.

The bedrock is well exposed in the summit cliff and farther downslope in a cliff band following contour lines, 12,070 and 12,100 feet (3,680 and 3,690 m.). Below this cliff band it is only partly visible. The detritus covering the bedrock, however, is shallow -- about 1.6 feet (1/2 m.) deep -- west of the line on the site plan marking the eastern edge of outcropping bedrock and following approximately a line that connects the mine shaft with point M2 and point W6. East of this line the bedrock may be too deep for construction purposes. The whole basin is well drained, and no particular difficulties from water seeps are expected.

10. Types of Structures Recommended for the Stanley Project

The analysis of the snow and terrain conditions (see Sect. 8, 9) show three different areas with regard to structural control possibilities. A different type of structure is recommended for each area. Two of the types, the wall-fence combination and the snow jack,[15] are special adaptations for Rocky Mountain conditions; the third is the heavy-duty snow bridge well known in European avalanche control areas.

10.1 Wall-Fence Combination

Because the steep, rugged summit cliff is very difficult to control, it is suggested that no structures be installed in this area. Instead, very heavy structures able to catch slides falling from the summit cliff should be built just below the cliff. Because of deep snowdrifts just below the summit cliff and in a narrow band along the west rim, such heavy structures have to be planned anyway. The area that shows more than 18 feet (5.5 m.) of snow depth should be controlled by a special type of supporting structure. The combination of a concrete wall (rib wall) with a fence fixed on top is suggested as a possible solution to the problem (fig. 31). This combination could withstand the enormous settling forces expected in the roll, because the vertical supporting plane of the fence minimizes this type of load. The concrete wall would be adequate to withstand the higher pressure forces in the lower portions of the snowpack.

Both the wall and the fence have been used in avalanche control projects. The combination of a fence atop a massive wall, however, is a unique arrangement suggested for snow roll areas where snow depths exceed 18 feet (5.5 m.).

10.2 Snow Bridges

Heavy snow bridges are recommended for areas on the lower part of the southeast slope (west of profile M1 - M3) where snow depths are expected to be between 10 and 16 feet (3-5 m.). The critical height for a steel snow bridge is between 16 and 20 feet (5-6 m.), depending on steepness of the slope at the site. Higher bridges cannot be constructed economically. Therefore, the critical snow depth for this type of structure was set at 18 feet (5.5 m.). In rolls deeper than 18 feet (5.5 m.), the wall-fence combination or another special type of structure should be used.

10.3 Snow Jacks

A special type of structure called the snow jack (fig. 32) is recommended for parts of the slope where bedrock is not within reach and where snow depths do not exceed 10 feet (3 m.); the more expensive conventional supporting structures are not very satisfactory unless they are anchored to bedrock.

The snow jack is a cheap, easy-to-install tripod built of steel angles (fig. 32). The downhill leg supports the two crossed uphill legs. Chain link fencing is attached to the two uphill legs by means of wire rope to form the supporting plane. Normally, several snow jacks would be connected by steel cables to form a continuous line across the slope. The transverse wire rope connectors are firmly anchored beyond the ends of each line of jacks, and the jacks are guyed on the uphill side. The wire rope guys are flexible, and allow the individual jacks to yield a little to snow pressures and, to a certain extent, to follow the movements of the unstable scree or talus. The stiff connection

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[15] *Frutiger, Hans. Suggestions for the design of two types of supporting structures to be used for avalanche control. June 1962. (Unpublished report on file at Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado.)*

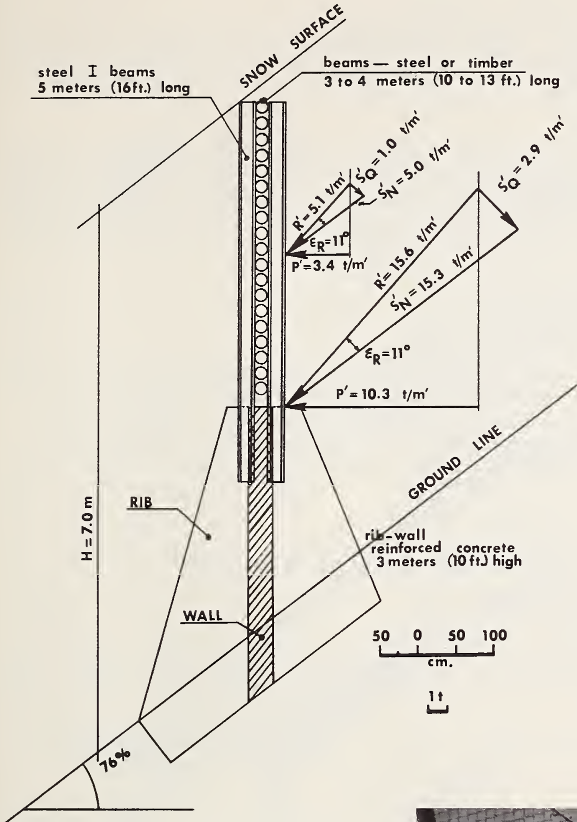

Figure 31.--The rib-wall with a steel fence on top. An especially heavy supporting structure for the control of deep snow accumulation in Stanley Project, Berthoud Pass, Colorado.

Figure 32.--The snow jack, a special supporting structure suggested for areas where bedrock is not within reach and where snow depths do not exceed 10 feet (3 m).

between the two uphill legs and the downhill support plus the flexibility of the whole structure makes it very hard to set up design criteria. Therefore, the dimensions of the members must be chosen somewhat intuitively. As a rough estimate, the snow pressures calculated for a snow bridge can be used.

Snow jacks are recommended for parts of the southeast slope of the Stanley Avalanche, west of profile M1 - M3, where snow depths do not exceed 10 feet (3 m.), and where bedrock is not within reach. Additional data are needed to determine if the south slope east of profile M1 - M3 should be controlled. If control is needed in this area, the snow jack is recommended since snow depths are never great.

10.4 Tests with Snow Drift Controls

Detailed suggestions of how to use drift controls in the Stanley project cannot be made. The deep snow accumulation in the roll raises some problems for control of this zone (see Sect. 8.1). It is obvious that drift control should be tested on the west rim. If it is possible to retain some snow up on the flat ridgetop, there would be less snow in the roll to the lee of the ridge, and the supporting structures would be relieved considerably. Therefore, the project should contain some snow fences, at least for testing purposes.

11. Arrangement of Structures for the Control of the Stanley Avalanche

11.1 Extent of the Area to be Controlled by Structures

Snow and terrain data gathered in preliminary surveys showed the following parts of the Stanley Avalanche area should be controlled:

	Acres	or hectares
> The summit cliff	0.45	0.18
> The southeast steep rim with snow depths over 18 feet (5.5 m.) -- roll	2.18	.88
> The southeast slope with snow depths between 13 and 18 feet (4.0 and 5.5 m.)	1.26	.51
> The southeast slope and west rim with snow depths less than 13 feet (4.0 m.).	1.11	.45
> The south slope, usually bare of snow	1.65	.67

11.2 Types of Structures and Arrangement

The summit cliff (fig. 33) should be controlled by the topmost line of wall-fence structures. This line of structures follows the contour line at 12,170 feet (3,710 m.). These structures will stop sluffs and slides originating in the summit cliffs. Such slides are not expected to be large since the cliffs are too steep and exposed to the wind to accumulate much snow.

The steep rim on which the roll builds up should be controlled by five more lines of the same type of structures. The second line of these structures would be located on top of the cliff band roughly following the contour at 12,105 feet (3,690 m.); the third line near the foot of the cliff band along the contour at 12,070 feet (3,680 m.). Both lines two and three would be about 300 feet (100 m.) long. Lines four to six would be shorter lines designed to control the crest of the roll where there is more than 18 feet (5.5 m.) of snow. These lines should be staggered downslope along the roll.

The lower portion of the southeast slope where 13 to 18 feet (4.0 to 5.5 m.) of snow are expected would be controlled by snow bridges of the European type.[14] 15 This area will take two lines

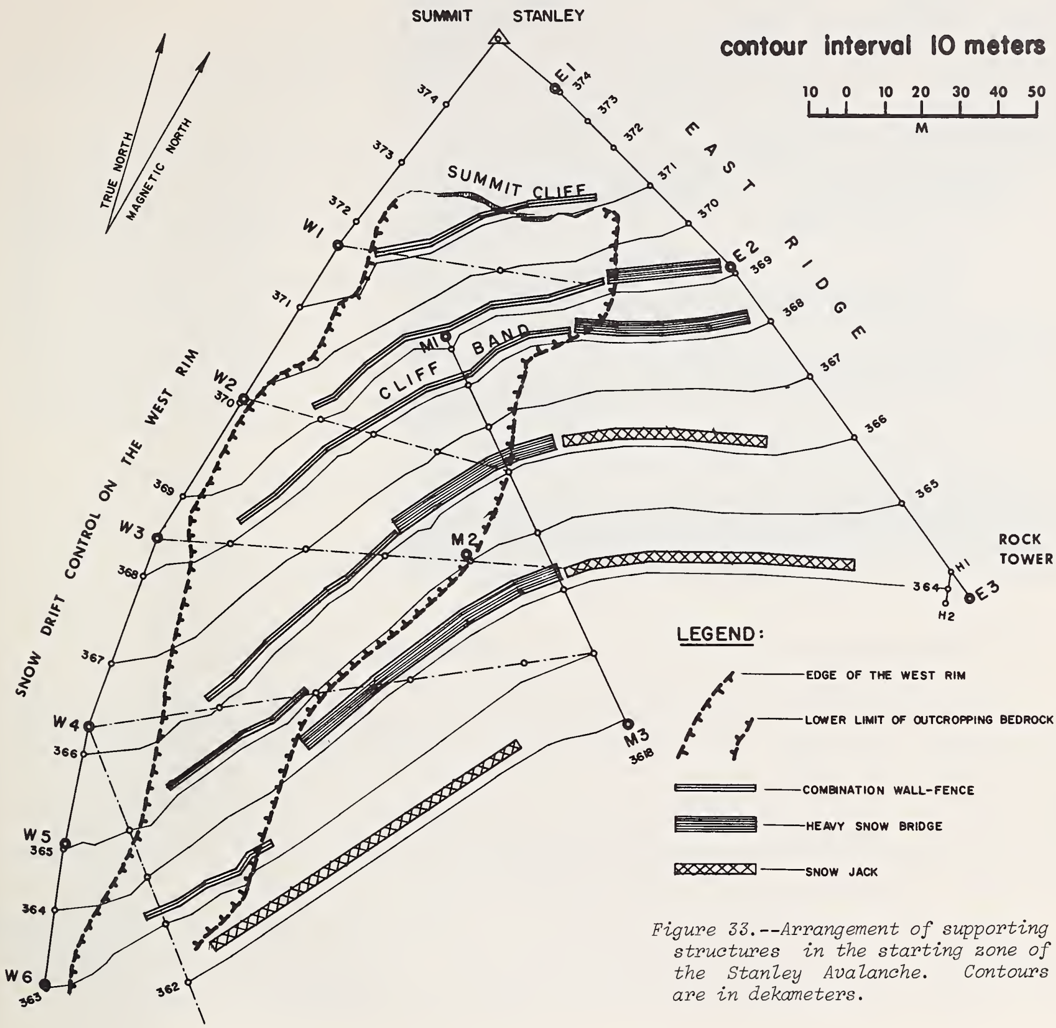

Figure 33.--Arrangement of supporting structures in the starting zone of the Stanley Avalanche. Contours are in dekameters.

of snow bridges, one 165 feet (50 m.) and the other 260 feet (80 m.) long. Below the snow bridges where snow depths are less than 13 feet (4.0 m.), there should be a line of snow jacks[15] about 330 feet (100 m.) long.

The south slope should be controlled at the top by two short lines of snow bridges following the contours at 12,105 and 12,070 feet (3,690 and 3,680 m.). The lines are 100 feet (30 m.) and 130 feet (40 m.) long. As mentioned earlier, there is some question whether control of the lower portion of the south slope is necessary. This report, however, provides for two lines of snow jacks 200 and 260 feet (60 and 80 m.) long until there is definite evidence showing they are not needed.

The continuous arrangement and relatively heavy concentration of snow bridges recommended above have been used in many European areas (fig. 34).

Figure 34.--Closely spaced, continuous lines of supporting structures provide maximum protection from avalanches. These prestressed concrete snow bridges are part of the Kühnihorn Avalanche control project above the village of St. Antönien, Switzerland.

11.3 Distance Between Lines of Structures, and Interval Between Structures

The recommended distance between lines of structures is shorter than it could be according to Guidelines (Art. 20, 21). The southeast slope has a gradient between 60 and 70 percent; 67 percent prevails. According to figure 21 of the Guidelines, the distance would be 180 feet (55 m.) by the formula $L = f_L \cdot H_K$ since f_L for a 70-percent slope is approximately 10 and H_K is 18 feet (5.5 m.). It is unreasonable to put the lines this far apart because of the slides and slabs that are very likely to occur in the steeper portions of the project area. For normal conditions, the distances should not be longer than 100 feet (30 m.), measured along the slope. For complete protection under all conditions, a 70-foot (20 m.) distance probably would be needed.

There are no natural barriers in the project area that would permit a greater interval between adjacent structures and therefore a savings of materials. The uniform slope favors a continuous arrangement. The wall-fence combination and the jacks are arranged continuously. The bridges can be installed with intervals between adjacent structures not exceeding 6 feet (2 m.).

11.4 Total Length of Structures, and Length of Structures Per Unit Area

Figure 33 shows the suggested arrangement of the different types of supporting structures to control the Stanley Avalanche. The total project area is 6.65 acres (2.69 ha.). The area protected by structures is 5 acres (2 ha.). On this area the following structures are suggested:

	Vertical height		Total length	
	(Feet	or meters)	(Feet	or meters)
Wall-fence combination	23	7.0	1,300	400
Snow bridges	18	5.5	650	200
Snow jacks	13	4.0	800	240
			2,750	840

The length of structures per unit area is 550 feet per acre (420 m. per ha.).

12. Design of Structures for the Stanley Project

12.1 Calculation of the Components of the Snow Pressure Force

The formulas that follow carry the same numbers, in brackets [ ], as those in the Guidelines. Since all formulas have been developed with the metric system, substitutions into them should use that system, then the final result may be converted to U. S. equivalents (feet; inches). For convenience, nomographs 1 through 4 with their related equations have been reproduced separately, and are enclosed in the pocket of the back cover.

12.11 Component Parallel to the Slope (S'_N)

Factors influencing snow pressure and the formula for the component of the snow pressure parallel to the slope, S'_N, are given below (see also Guidelines, Arts. 25, 27, 52). Of course, the validity of this formula for Rocky Mountain conditions must be checked. It is evident that snow conditions in the Swiss Alps differ considerably from those in the Colorado Rockies.

Based on field observations in Colorado and experience elsewhere, the following snow conditions can be used for the Stanley Avalanche:

γ_S - average snow density . . . . . 0.4 t/m^3

H_S - snow depth at the structure site . . 2 to 6 m

K - creep factor [Art. 27]

ψ - slope angle = 76% or 37°

$\sin 2\psi = 0.96$

$K = 0.83 \times 0.96 = 0.8$

N - glide factor N = 2.4 [Art. 25,7]

f_C - altitude factor $f_C = 1.3$ [Art. 25,6]

An estimate of S'_N, in tons per running meter, is given by the following formula, which sets the snow depth equal to the maximum height of the structure but assumes a relative low snow density of $\gamma_H = 0.270\ t/m^3$.

$$\boxed{S'_N = 0.10 \cdot H^2 \cdot N \cdot f_C}$$ [Art. 52,1]

with the above formula --

for a snow depth of 2 m.: $S'_N = 0.1 \times 2^2 \times 2.4 \times 1.3 = 1.2$ t/m' (805 lbs./ft.)

for a snow depth of 6 m.: $S'_N = 0.1 \times 6^2 \times 2.4 \times 1.3 = 11.2$ t/m' (7,515 lbs./ft.)

Snow bridges with a vertical height of 5.5 m. (18 ft.) will be subject to a snow pressure parallel to the slope of about 10 tons per linear meter (6,710 pounds per foot) during the winter months when the snow is still light.

12.12 Component Perpendicular to the Slope (S'_Q)

The component of the snow pressure perpendicular to the slope is:

$$\boxed{S'_Q = S'_N \cdot \frac{a}{N \cdot \mathrm{tg}\,\psi}}$$ [Art. 28,1; 52,2]

where: $N \times tg\psi = 2.4 \times 0.76 = 1.8$ for a slope of 76% (37°) and a glide factor of 2.4; in the equation, a is a dimensionless number that varies from 0.5 for a light new snow to 0.0 for dense, old, settled snow (table 3).

Table 3.--S'_Q values corresponding to several values of S'_N for two values of a

S'_N		S'_Q if a = 0.35		S'_Q if a = 0.50	
t/m'	lb./ft.	t/m'	lb./ft.	t/m'	lb./ft.
1.2	805	0.2	135	0.3	200
1.5	1,005	.3	200	.4	270
10.0	6,710	1.9	1,275	2.8	1,880
11.2	7,515	2.2	1,475	3.1	2,080
13.8	9,260	2.7	1,810	3.8	2,550

12.13 End Effect Forces (S'_R)

An additional force must be taken into consideration at the free ends of single structures as well as at the free ends of lines of structures. This end effect force, S'_R, is given by the following formula:

$$\boxed{S'_R = f_R \cdot S'_N} \qquad \text{[Art. 52,5]}$$

where the end effect factor f_R is given by formula:

$$\boxed{f_R = (0.92 + 0.65 \cdot N)\,\frac{A}{2} \leqslant (1.00 + 1.25 \cdot N)} \qquad \text{[Art. 52,6]}$$

with-- A (interval between structures) = 2 m.

$N = 2.4$

$$f_R = (0.92 + 0.65 \times 2.4)\,\frac{2}{2} = 2.5$$

When f_R is 2.5, the end effect forces, S'_R, for several values of S'_N are:

S'_N (t/m'	or lb./ft.)	S'_R (t/m'	or lb./ft.)
1.2	805	3.0	2,015
10.0	6,710	25.0	16,775
13.8	9,260	34.5	23,150

12.2 Application of Calculated Snow Pressures for Types of Structures Suggested

12.21 Wall-Fence Structure

Figures 28 and 29 show maximum snow depths from 1 winter's observation (1961-62). In profile I (fig. 28) more than 33 feet (10 m.) of snow was measured. The other three profiles, however, show maximum snow depth to be only slightly above 20 feet (6 m.). This maximum is reached only in a narrow strip 16 to 33 feet (5 to 10 m.) wide and 650 feet (200 m.) long along the west rim. For this reason it is not necessary to provide a fence high enough to penetrate the maximum snow depth of profile I. A wall-fence with a total height of 23 feet (7 m.) is recommended (see Sect. 10.1).

How strong must this wall-fence be? Formulas for the determination of the snow pressure given in the Guidelines cannot be applied without reservation, since they apply to "a unit length of an infinitely long supporting plane erected perpendicular to the slope ... " (Art. 27,1) and the fence is vertical. The concrete wall (see fig. 31) should be strong enough to support the component of S'_N perpendicular to the structure when S'_N is calculated for a snow depth of 23 feet (7.0 m.). For the steel fence (see fig. 31), this component would be calculated for a snow depth of only 13 feet (4.0 m.). The pertinent factors for the Stanley area are:

Extreme vertical snow depth for wall	H = 7.0 m. (23 feet)
Extreme vertical snow depth for fence	H = 4.0 m. (13 feet)
Glide factor	N = 2.4
Altitude factor	f_C = 1.3
Angle of slope	ψ = 76%
Arrangement	Continuous structures

-- FOR A SNOW DEPTH OF 7.0 METERS (23 FEET) --

$$S'_N = 0.10 \times H^2 \times N \times f_C \qquad \text{[Art. 52,1]}$$

$$S'_N = 0.1 \times 7.0^2 \times 2.4 \times 1.3 = 15.3 \text{ t/m'} \qquad \text{(10,265 lbs./ft.)}$$

$$S'_Q = S'_N \times \frac{a}{N \times tg\psi} \qquad \text{[Art. 52,2]}$$

when a = 0.35

$$S'_Q = 15.3 \times \frac{0.35}{2.4 \times 0.76} = 2.9 \text{ t/m'} \qquad \text{(1,950 lbs./ft.)}$$

Then, if R' is the vector sum of $S'_N + S'_Q$

$$R' = \sqrt{(15.3)^2 + (2.9)^2} = 15.6 \text{ t/m'} \qquad \text{(10,470 lbs./ft.)}$$

Now, the tangent of the angle ϵ_R between resultant R', and S'_N can be expressed as

$$tg\,\epsilon_R = \frac{S'_Q}{S'_N} = \frac{2.9}{15.3} = 0.1895 \quad \text{and} \quad \epsilon_R = 11° \qquad \text{[Art. 52,3]}$$

-- FOR A SNOW DEPTH OF 4.0 METERS (13 FEET) --

$$S'_N = 0.1 \times 4.0^2 \times 2.4 \times 1.3 = 5.0 \text{ t/m'} \qquad \text{(3,355 lbs./ft.)} \qquad \text{[Art. 52,1]}$$

$$S'_Q\ (a = 0.35) = 5.0 \times \frac{0.35}{2.4 \times 0.76} = 1.0 \text{ t/m'} \qquad \text{(670 lbs./ft.)} \qquad \text{[Art. 52,2]}$$

$$R' = \sqrt{5.0^2 + 1.0^2} = 5.1 \text{ t/m'} \qquad \text{(3,420 lbs./ft.)}$$

$$tg\,\epsilon_R = \frac{S'_Q}{S'_N} = \frac{1.0}{5.0} = 0.2000 \quad \text{and} \quad \epsilon_R = 11° \qquad \text{[Art. 52,3]}$$

The load P' per running meter and perpendicular to the fence is determined graphically, in figure 31:

P' (7.0 m.) = 10.3 t/m' (6,910 lbs./ft.)

P' (4.0 m.) = 3.4 t/m' (2,280 lbs./ft.)

12.22 Snow Bridge

The snow bridge commonly used in Europe has a grate with an effective height, D_K, of between 3.0 and 4.0 meters (10 and 13 feet), and a length, l, of 4.0 meters (13 feet). The following factors apply to the Stanley project area:

Extreme vertical snow depth	$H = 5.5$ m. (18 feet)
Extreme thickness of the snow cover	$D = 4.4$ m. (14.5 feet)
Glide factor	$N = 2.4$
Altitude factor	$f_C = 1.3$
Angle of slope	$\psi = 76\%$
Length of structure	$l = 4.0$ m. (13 feet)
Angle between the supporting plane and a plane perpendicular to the slope	$\varrho = 15°$
Interval between single structures	$A = 2.0$ m. (6.5 feet)

12.221 Snow pressure for the first type of loading.--The first type of loading (fig. 35) takes the stability of the whole structure into special consideration. Therefore, the line of action of the resultant of the snow pressure forces is assumed more or less parallel to the slope, with the point of application at half the height of the snowpack.

$$S'_N = 0.10 \times H^2 \times N \times f_C \qquad \text{[Art. 52,1]}$$

$$S'_N = 0.1 \times 5.5^2 \times 2.4 \times 1.3 = 9.4 \text{ t/m'} \qquad \text{(6,310 lbs./ft.)}$$

$$S'_Q = S'_N \times \frac{a}{N \operatorname{tg} \psi} \qquad \text{[Art. 52,2]}$$

$$S'_Q \ (a = 0.35) = 9.4 \times \frac{0.35}{2.4 \times 0.76} = 1.8 \text{ t/m'} \qquad \text{(1,210 lbs./ft.)}$$

$$S'_Q \ (a = 0.50) = 9.4 \times \frac{0.50}{2.4 \times 0.76} = 2.6 \text{ t/m'} \qquad \text{(1,745 lbs./ft.)}$$

The weight of the snow prism adjacent to the sloping grate of the snow bridge is given by:

$$\boxed{G' = 0.150 \cdot D^2 \cdot \operatorname{tg} \varrho} \qquad \text{[Art. 52,4]}$$

$$G' = 0.15 \times 4.4^2 \times 0.268 = 0.8 \text{ t/m'} \qquad \text{(535 lbs./ft.)}$$

The components of G' are given by:

$$G'_N = G' \sin\psi = 0.8 \times 0.60 = 0.5 \text{ t/m'} \qquad \text{(335 lbs./ft.)}$$

and

$$G'_Q = G' \cos\psi = 0.8 \times 0.80 = 0.6 \text{ t/m'} \qquad \text{(405 lbs./ft.)}$$

To calculate the end effects force, S'_R, it is necessary to first compute the end effect factor, f_R, which is expressed as:

$$f_R = (0.92 + 0.65 \times N) \frac{A}{2} \qquad \text{[Art. 52,6]}$$

$$= (0.92 + 0.65 \times 2.4) \frac{2}{2} = 2.5$$

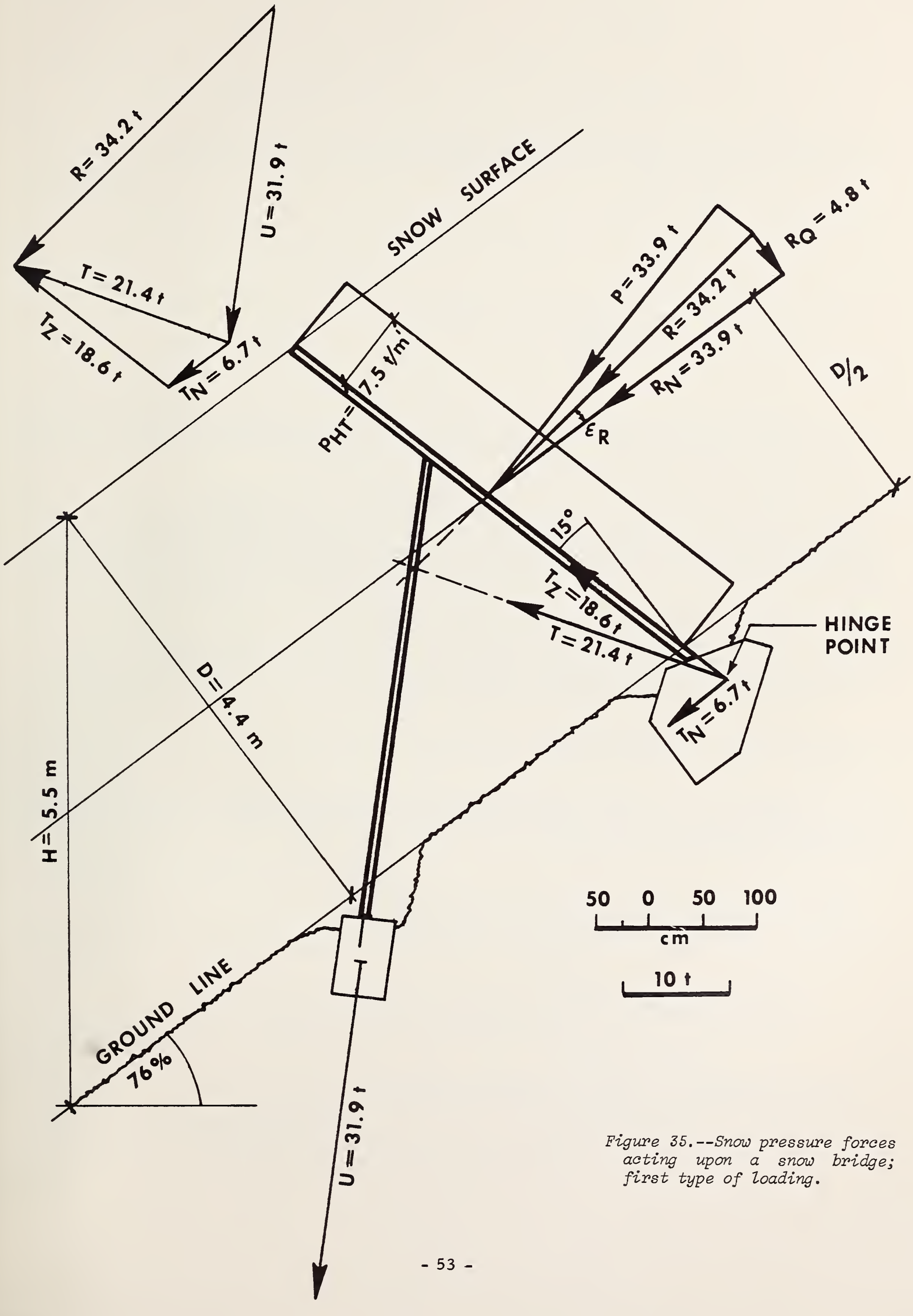

Figure 35.--Snow pressure forces acting upon a snow bridge; first type of loading.

The end effect force is given by:

$S'_R = f_R \times S'_N$ [Art. 52,5]

$S'_R = 2.5 \times 9.4 = 23.5\ t/m'$ (15,770 lbs. /ft.)

The end effect force operates over the length Δl where

$$\boxed{\Delta l = 0.60 \cdot \frac{A}{2} \leqslant \frac{D}{3}}$$ [Art. 52,7]

$\Delta l = 0.60 \times \frac{2}{2} = 0.6$ m. (2 ft.)

The total end effect force parallel to the slope is:

$S_R = S'_R \times \Delta l = 23.5 \times 0.6 = 14.1$ t

Snow pressure forces used for designing the trestle are usually calculated for only half of the bridge length, since the total load on the grate is supported equally by the two trestles. The resultant force parallel to the slope for half of the grate is:

$$R_N = \left(S'_N + G'_N\right) \frac{l}{2} + S_R = (9.4 + 0.5)\ \frac{4}{2} + 14.1 = 33.9\ t$$

Generally the trestle is designed for the pressure perpendicular to the slope calculated with a = 0.35.

$$R_Q = \left(S'_Q + G'_Q\right) \frac{l}{2} = (1.8 + 0.6)\ \frac{4}{2} = 4.8\ t$$

$$R = \sqrt{R'^2_N + R'^2_Q} = \sqrt{33.9^2 + 4.8^2} = 34.2\ t$$

$$\text{tg}\ \epsilon_R = \frac{R'_Q}{R'_N} = \frac{4.8}{33.9} = 0.1416; \quad \epsilon_R = 8°$$

Figure 35 is a diagram of the calculated forces. For the case of separate footings and a support with hinges on both ends, the loadings on the support and the footings can be determined graphically as follows:

Extend the line of action of R until it intersects the support. This intersection and the hinge point in the beam footing give the line of action of T.

Now draw a force diagram as follows: (see upper left corner of fig. 35)

Choose an arbitrary point and draw R to scale and properly alined.
From the same point, draw U of indefinite length but properly alined.
Draw T from the lower end of vector R until it intersects U, using the alinement described above.

Project components T_Z and T_N to the force diagram.

Determine the magnitude of U, T, T_Z, and T_N by scaling the force diagram.

The load on the beam footing is: $U = 31.9$ t

The tension force in the beam footing is: $T = 21.4$ t

with components $T_Z = 18.6$ t and $T_N = 6.7$ t.

The maximum bending moment on the beam at the point where the support is attached can be calculated from the load per unit length of the beam. The load perpendicular to the beam is:

$$P = R \cdot \cos(\varrho - \varepsilon_R) \qquad \text{[Art. 55,1]}$$

$$= 34.2 \times \cos 7° = 33.9 \text{ t}$$

The length of the beam is:

$$B_K = \frac{D}{\cos \varrho} = \frac{4.4}{0.966} = 4.5 \text{ m.} \qquad \text{(15 feet)}$$

and the load per unit length of the beam is:

$$p_{HT} = \frac{P}{B_K} = \frac{33.9}{4.5} = 7.5 \text{ t/m}' \qquad \text{(5,035 lbs./ft.)}$$

12.222 Snow pressure for the second type of loading.--The second type of loading (fig. 36) occurs in spring after the snowpack has settled. The decrease in snow depth is accompanied by an increase in snow density. After the snow has settled, the load on the grate is the same as in the first type of loading, but the resultant has a lower point of application and the specific snow pressure is higher.

The entire grate is designed for the specific load caused by the second type of loading, even though the top part of the grate is free of snow in late spring (see Sect. 7). This is done to be sure the grate will be strong enough to absorb the forces caused by possible dynamic loading from sluffs and the very unequal distribution of snow pressure on the grate.

The extra force mentioned in the Guidelines (Art. 55,3) must also be considered. This amounts to 25 percent of the specific snow pressure, p_h, calculated for parts of the grate when there are no end effect forces. This extra force is intended to account for high pressures caused by pronounced gliding when an early snow falls on warm ground and the uneven loading in spring when irregular melting results in the snow receding from all but the lower parts of the grate. The force is active over the whole length of the supporting plane from the ground up to one-quarter of the height.

The loading is determined graphically in figure 36 by the procedure described in Section 12.221. The load on the support and the support footing is $U = 25.6$ t. The tension force in the beam footing is:

$T = 20.8$ t

with components $T_Z = 13.9$ t and $T_N = 12.3$ t.

The load per unit length of the beam for the second type of loading is:

$$p_{hT} = \frac{P}{0.77 \times B_K} = 9.8 \text{ t/m}' \qquad \text{(6,575 lbs./ft.)} \qquad \text{[Art. 55,2]}$$

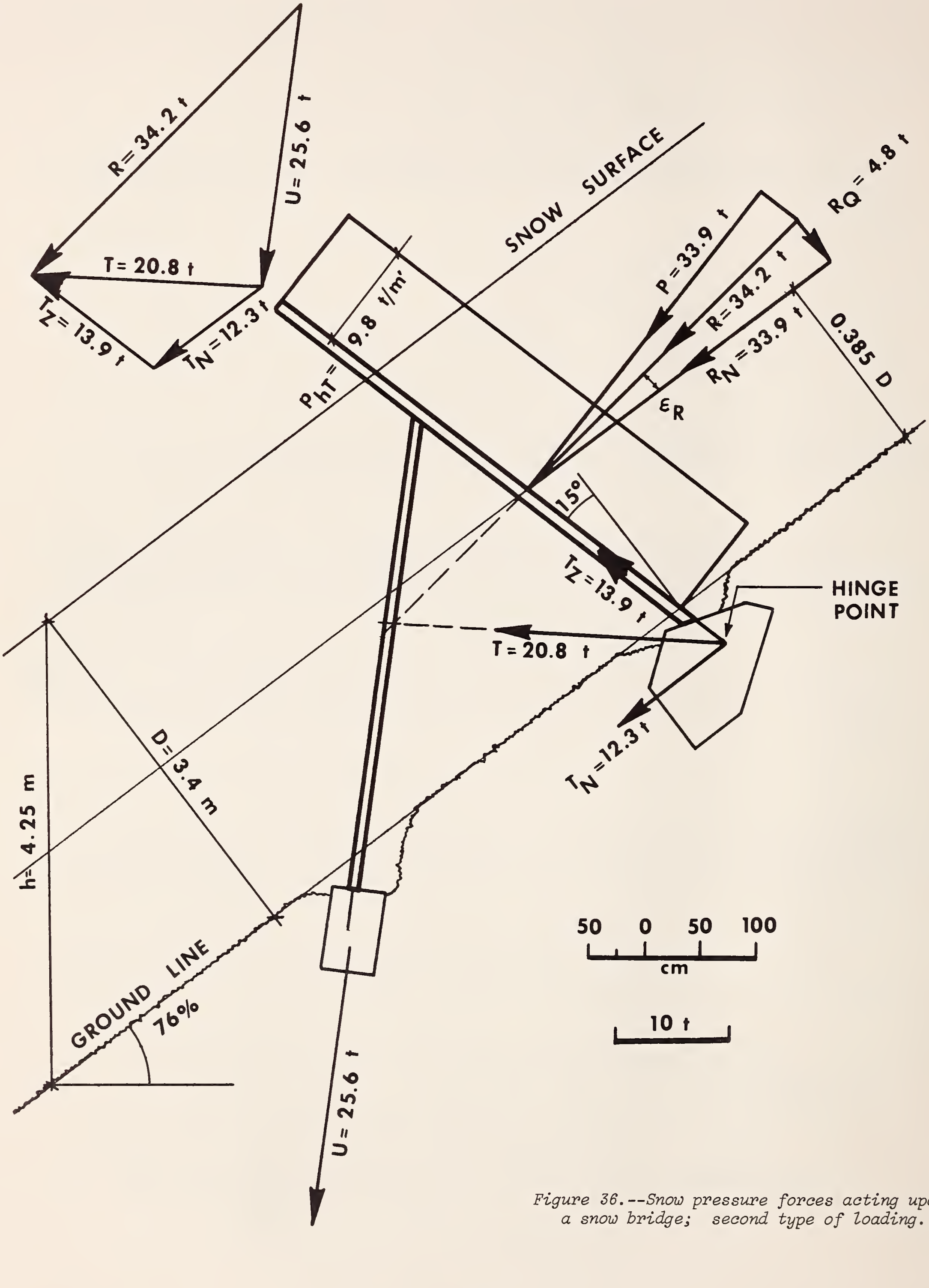

Figure 36.--Snow pressure forces acting upon a snow bridge; second type of loading.

In designing the grate of a snow bridge, two specific loadings, p_h, are calculated: one for the section of the grate where end-effect forces are acting; another for the section where there are no end-effect forces (fig. 37).

-- WHEN END-EFFECT FORCES ARE PRESENT --

$R'_N = S'_N + S'_R + G'_N = 9.4 + 23.5 + 0.5 = 33.4$ t/m' (22,410 lbs./ft.)

R'_Q $(a = 0.35) = S'_Q + G'_Q = 1.8 + 0.6 = 2.4$ t/m' (1,610 lbs./ft.)

$R' = \sqrt{33.4^2 + 2.4^2} = 33.5$ t/m' (22,480 lbs./ft.)

$\mathrm{tg}\ \epsilon_R = \frac{2.4}{33.4} = 0.072; \quad \epsilon_R = 4°$

$P' = R' \times \cos(\varrho - \epsilon_R) = 33.5 \times \cos(15° - 4°) = 32.8$ t/m' (22,010 lbs./ft.) [Art. 55,1]

$p_h = \frac{P'}{0.77 \times B_K} = \frac{32.8}{0.77 \times 4.5} = 9.5$ t/m^2 (1,950 lbs./sq. ft.) [Art. 55,2]

-- WHEN END-EFFECT FORCES ARE ABSENT --

$R'_N = S'_N + G'_N = 9.4 + 0.5 = 9.9$ t/m' (6,645 lbs./ft.)

$R'_Q = S'_Q + G'_Q = 1.8 + 0.6 = 2.4$ t/m' (1,610 lbs./ft.)

$R' = \sqrt{9.9^2 + 2.4^2} = 10.2$ t/m' (6,845 lbs./ft.)

$\mathrm{tg}\ \epsilon_R = \frac{R'_Q}{R'_N} = \frac{2.4}{9.9} = 0.242; \quad \epsilon_R = 14°$

$P' = R' \times \cos(\varrho - \epsilon_R) = 10.2 \times \cos(15° - 4°) = 10.2$ t/m' (6,845 lbs./ft.) [Art. 55,1]

$p_h = \frac{P'}{0.77 \times B_K} = \frac{10.2}{0.77 \times 4.5} = 2.9$ t/m^2 (595 lbs./sq. ft.) [Art. 55,2]

The extra force mentioned on page 55 and in Guidelines (Art. 55,3) is equal to:

$0.25 \times p_h$ or $0.25 \times 2.9 = 0.7$ t/m^2 (145 lbs./sq. ft.)

The individual bars on the grate should be designed for a transverse loading no smaller than the q_B given in formula 57,4 of the Guidelines. If the transverse loading computed from the procedures outlined in the Guidelines (Art. 57,2 and 57,3) is larger than the minimum value computed with formula 57,4, use the larger loading.

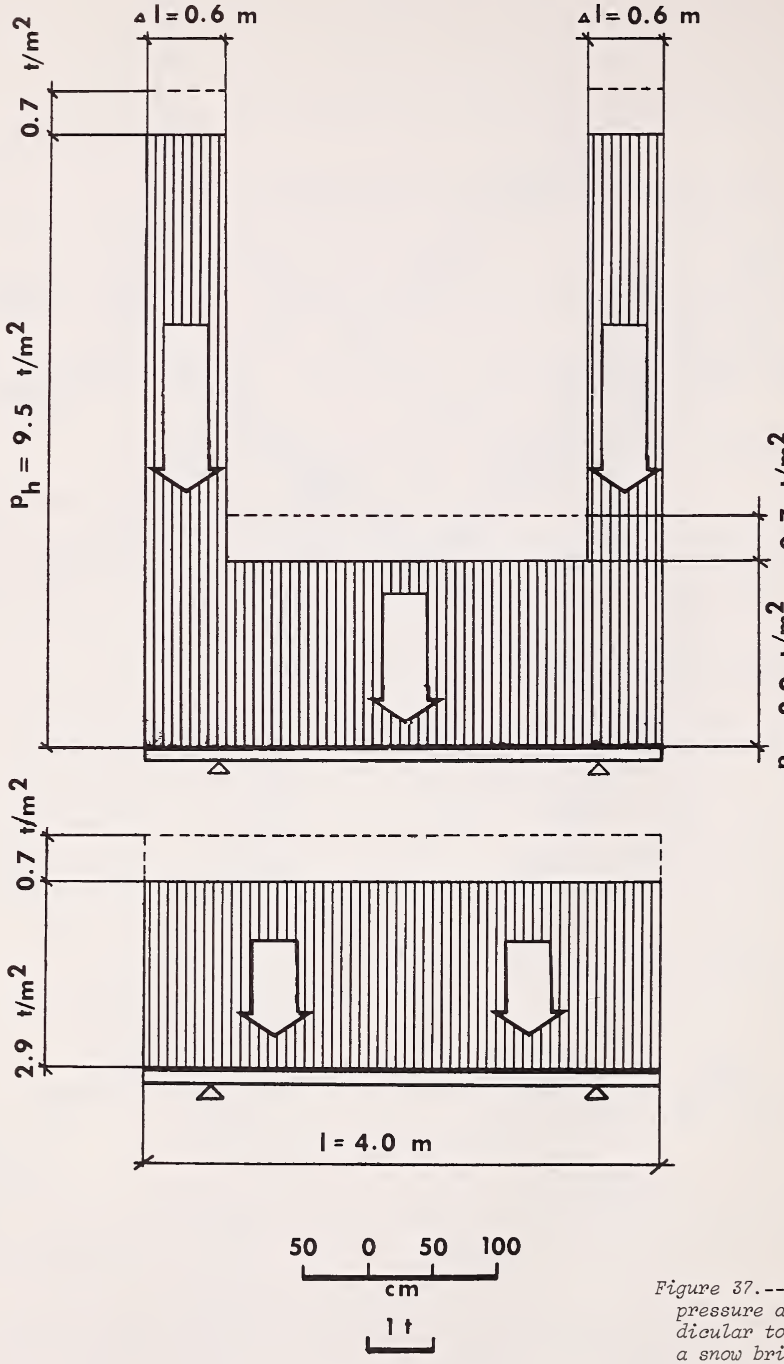

Figure 37.--Specific snow pressure acting perpendicular to the grate of a snow bridge. Above: with end-effect forces; below: without end-effect forces.

$R'_N = S'_N + S'_R + G'_N = 9.4 + 23.5 + 0.5 = 33.4$ t/m' (22,410 lbs./ft.) [Art. 31,4]

R'_Q (a = 0.50) $= S'_Q + G'_Q = 2.6 + 0.6 = 3.2$ t/m' (2,150 lbs./ft.) [Art. 31,2]

$R' = \sqrt{R'^2_N + R'^2_Q} = \sqrt{33.4^2 + 3.2^2} = 33.5$ t/m' (22,480 lbs./ft.) [Art. 31,3]

$\text{tg}\,\epsilon_R = \frac{R'_Q}{R'_N} = \frac{3.2}{33.4} = 0.096; \quad \epsilon_R = 5.5°$ [Art. 31,5]

$Q = R' \times \sin(\epsilon_R - \varrho)$ [Art. 57,1]

$= 33.5 \times \sin(5.5 - 15)$

$= 33.5 \times 0.165 = 5.5$ t/m' (3,690 lbs./ft.)

$q_h = \frac{Q'}{0.77 \times B_K} = \frac{5.5}{0.77 \times 4.5} = 1.6 \text{ t/m}^2$ (330 lbs./sq. ft.) [Art. 57,2]

$q_B = q_h \times b$ [Art. 57,3]

letting b = 0.3 m. (1 ft.)

$q_B = 1.6 \times 0.3 = 0.5$ t/m' (335 lbs./ft.)

The minimum load for a bar is:

$q_B = 0.20\, p_B$ where $p_B = p_h \times b$ [Art. 57,4]

$q_B = 0.20\,(9.5)\,(0.3) = 0.6$ t/m' (405 lbs./ft.)

Hence, individual bars of the grate should be designed for a transverse loading of about 0.6 t/m' (405 lbs./ft.)

12.23 Snow Jack

As mentioned in Section 10.3, specific design criteria have not yet been developed for snow jacks. As a first approximation, they should be designed to withstand the snow pressure forces expected on a snow bridge at the site. Further suggestions for the design of snow jacks have been included in an office report. [16]

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[16] *See footnote 15, p. 44.*

LITERATURE CITED

Bader, Henri.
1962. The physics and mechanics of snow as a material.* 79 pp. In Part II, Sect. B, Cold Regions Sci. and Eng. Phys. Sci. edited by F. J. Sanger. U. S. Army Materiel Command, Cold Regions Res. and Eng. Lab., Corps Eng., Hanover, N.H.

_______, Haefeli, R., Bucher, E., and others.
1939. Der Schnee und seine Metamorphose. Beitr. zur Geol. der Schweiz, Geotechnische Ser., Hydrol., Lieferung 3, Bern. [Snow and its metamorphism.* 1954. Transl. 14, 313 pp., illus. Snow, Ice and Permafrost Res. Estab., Corps Eng., U. S. Army, Wilmette, Ill.]

Bucher, E.
1948. Beitrag zu den theoretischen Grundlagen des Lawinenverbaus. Beitr. zur Geol. der Schweiz, Geotechnische Ser., Hydrol., Lieferung 6, Bern. [Contribution to the theoretical foundations of avalanche defense construction.* 1956. Transl. 18, 109 pp., illus. Snow, Ice and Permafrost Res. Estab., Corps Eng., U. S. Army, Wilmette, Ill.]

de Quervain, M.
1957. Avalanche classification. Union Geod. and Geophys. Int. Gen. Assem., Toronto. Int. Ass. Sci. Hydrol. Pub. 46, pp. 387-392.

_______ and Figilister, R.
1953. Zum Schneedruckproblem.* Winterbericht 1951/52. Nr. 16, S. 89-98. Eidg. Inst. für Schnee- und Lawinenforschung, Weissfluhjoch/Davos, Schweitz. [The problem of snow pressure. Winter report 1951-52. No. 16, pp. 89-98, illus. Swiss Fed. Inst. for Snow and Avalanche Res. Pub. in German and French.]

Frutiger, Hans.
1961. Über den gegenwärtigen Stand der Lawinenverbauung mit Schneenetzen.* Winterbericht 1959/60. Nr. 24, S. 133-144. Eidg. Inst. für Schnee-und Lawinenforschung, Weissfluhjoch/Davos, Schweitz. [The present state of avalanche control with snow nets. Winter report, 1959-60. No. 24, pp. 133-144, illus. Swiss Fed. Inst. for Snow and Avalanche Res. Pub. in German and French.]

_______ 1964. Snow avalanches along Colorado mountain highways.* U. S. Forest Serv. Res. Paper RM-7, 85 pp., illus. Rocky Mountain Forest and Range Exp. Sta., Ft. Collins, Colo.

_______ and de Quervain, M.
1964. Stützverbau oder Galerie?* In Zum Winterdienst auf Strassen, S. 17-18. Eidg. Inst. für Schnee- und Lawinenforschung, Weissfluhjoch/Davos, Schweitz. Separatdruck aus Strasse und Verkehr, Nr. 1/1964. [Supporting structures or galleries? In Report of winter road conditions, pp. 17-18, illus. Swiss Fed. Inst. for Snow and Avalanche Res. Reprinted from Streets and Traffic, No. 1, 1964.] (See English translation in appendix.)

Guler, K.
1959. Moyens modernesde stabilisation de la couche de neige. Aluminium Suisse, No. 1, pp. 8-43. [Modern measures to stabilize the snowpack.]

Hanausek, Erich.
1960. Fünf Jahre Lawinenverbauung mit Ganzstahlkonstruktion am Heuberg bei Häselgehr (Österreich). Bundnerwald, Jahrg. 13, Nr. 5, S. 117-127. Druck und Expedition: Bischofberger & Co., Chur. [Five years of avalanche control by steel structures at the Heuberg near Häselgehr, Austria. Bundnerwald 13(5): 117-127, illus. Publishers: Bischofberger and Co., Chur.]

Hasler AG
1954. Lawinenmelde-Anlage Mahnkinn.* Hasler-Mitt. Nr. 1, 7 S. Bern. [Avalanche warning at Mahnkinn. Hasler Company Report No. 1, 7 pp., illus.]

Hopf, J., and Bernard, J.
1963. 1. Windbeeinflussende Bauten in der Lawinenverbauung und -vorbeugung. In Teil II. Ökologische Untersuchungen in der subalpinen Stufe zum Zwecke der Hochlagenaufforstung.* Mitt. Forstl. Bundes-Versuchsanstalt Mariabrunn in Wien-Schönbrunn. Heft 60, 607-632. [1. Wind baffles in avalanche control and prevention. In Part II. Ecological investigations of the subalpine zone for the purpose of high altitude afforestation. Rep. Fed. Forest Exp. Inst. Mariabrunn at Vienna-Schönbrunn. Issue 60, pp. 607-632, illus.]

Hult, Ruby El.
1960. Northwest disaster; avalanche and fire. 228 pp., illus. Portland, Ore.: Binfords and Mort.

In der Gand, H. R.
1954. Beitrag zum Problem des Gleitens der Schneedecke auf dem Untergrund.* Winterbericht 1952/53. Nr. 17, S. 103-117. Eidg. Inst. für Schnee- und Lawinenforschung, Weissfluhjoch/Davos, Schweitz. [The problem of the gliding of the snowpack on the ground surface. Winter report, 1952-53. No. 17, pp. 103-117, illus. Swiss Fed. Inst. for Snow and Avalanche Res. Pub. in German and French.]

_______ 1957. Ergebnisse der Gleitmessung.* Winterbericht 1955/56. Nr. 20, S. 111-114. Eidg. Inst. für Schnee- und Lawinenforschung, Weissfluhjoch/Davos, Schweitz. [Results of glide measurements. Winter report 1955-56. No. 21, pp. 111-114, illus. Swiss Fed. Inst. for Snow and Avalanche Res. Pub. in German and French.]

_______ 1959. Ergebnisse der Gleitmessung.* Winterbericht 1957/58. Nr. 22, S. 122-126. Eidg. Inst. für Schnee- und Lawinenforschung, Weissfluhjoch/Davos, Schweitz. [Results of glide measurements. Winter report 1957-58. No. 22, pp. 122-126, illus. Swiss Fed. Inst. for Snow and Avalanche Res. Pub. in German and French.]

Judson, Arthur.
1965. The weather and climate of a high mountain pass in the Colorado Rockies.* U. S. Forest Serv. Res. Paper RM-16, 28 pp., illus. Rocky Mountain Forest and Range Exp. Sta., Ft. Collins, Colo.

LaChapelle, E. R.
1960. Recent progress in North American avalanche forecasting and control. J. Glaciol. 3: 679-685, illus.

MacLean, J. D.
1952. Preservative treatment of wood by pressure methods. U. S. Dep. Agr., Agr. Handb. 40, 160 pp., illus.

Marr, James C.
1940. Snow surveying. U. S. Dep. Agr. Misc. Pub. 380, 45 pp., illus.

Martinelli, M. Jr.
1960. Creep and settlement in an alpine snowpack.* U. S. Forest Serv. Rocky Mountain Forest and Range Exp. Sta. Res. Note 43, 4 pp., illus. Ft. Collins, Colo.

Roch, A.
1962. Mesure de la force des avalanches.* Winterbericht 1960/61. Nr. 25, S. 124-136. Eidg. Inst. für Schnee- und Lawinenforschung, Weissfluhjoch/Davos, Schweitz. [The magnitude of avalanche forces. Winter report 1960-61. No. 25, pp. 124-136, illus. Swiss Fed. Inst. for Snow and Avalanche Res. Pub. in German and French.]

*Address requests for copies to the originating office.

______ 1964. Possibilités de protection en déviant ou en freinant l'avalanche, ou par déclenchement artificiel.* In Zum Winterdienst auf Strassen, S. 18-21. Eidg. Inst. für Schnee- und Lawinenforschung, Weissfluhjoch/Davos, Schweitz. Separatdruck aus Strasse und Verkehr, Nr. 1/1964. [Possibilities of protection by deflecting or braking avalanches or by artificial release. In Report of winter road conditions, pp. 18-21, illus. Swiss Fed. Inst. for Snow and Avalanche Res. Reprinted from Streets and Traffic No. 1, 1964.]
(See English translation in appendix.)

______ and Sommerhalder, E.
1961. Comportement de divers types d'ouvrages de stabilisation de la neige.* Winterbericht 1959/60.Nr. 24, S. 128-133. Eidg. Inst. für Schnee- und Lawinenforschung, Weissfluhjoch/Davos, Schweitz. [The behavior of different types of snow stabilization structures. Winter report 1959-60. No. 24, pp. 128-133, illus. Swiss Fed. Inst. for Snow and Avalanche Res. Pub. in German and French.]

Salm, B., and Sommerhalder, E.
1964. Beanspruchung von Lawinenschutzgalerien durch Schnee.* In Zum Winterdienst auf Strassen, S. 9-16. Eidg. Inst. für Schnee- und Lawinenforschung, Weissfluhjoch/Davos, Schweitz. Separatdruck aus Strasse und Verkehr, Nr. 1/1964. [Snow pressure on avalanche protection sheds. In Report of winter road conditions, pp. 9-16, illus. Swiss Fed. Inst. for Snow and Avalanche Res. Reprinted from Streets and Traffic No. 1, 1964.]

Schaerer, Peter [A.]
1960. The avalanche defence on the Trans-Canada Highway at Rogers Pass. West. Snow Conf. Proc. 28: 71-78, illus.

______ 1962a. The avalanche hazard evaluation and prediction at Rogers Pass.* Div. Build. Res. Tech. Paper 142, (NRC 7051), 32 pp., illus. Nat. Res. Counc., Ottawa, Canada.

______ 1962b. Planning avalanche defence works for the Trans-Canada highway at Rogers Pass, B. C. Eng. J. 45(3): 31-38, illus. (Reprinted as Div. Build. Res. Res. Paper 152, (NRC 6732),*12 pp., illus. Nat. Res. Counc., Ottawa, Canada.)

______ 1965. Snowshed location and design.* ASCE Transp. Eng. Conf. Preprint 215, 27 pp., illus. (Preprinted by Nat. Res. Counc., Ottawa, Canada.)

Schild, M.
1955. Über die Entstehung der Lawinenbulletins. Die Alpen, Nr. 4/1955, S. 15-18. Bern: Stämpfli and Cie. [About the origin of the avalanche bulletins. The Alps 1955(4): 15-18, illus.]

______ 1957. Sprengfelder zur Auslösung von Lawinen.* Mitt. Nr. 13, 12 S. Eidg. Inst. für Schnee- und Lawinenforschung, Weissfluhjoch/Davos, Schweitz. [Mine fields to trigger avalanches. Rep. No. 13, 12 pp., illus. Swiss Fed. Inst. for Snow and Avalanche Res. Pub. in German and French.]

Schwarz, W.
1960. Bremsverbauungen. Schweiz. Z. Forstwesen, Nr. 1, S. 41-54. [Braking structures. Swiss Forestry Magazine No. 1, pp. 41-54, illus.]
(See English translation in appendix.)

Seligman, G.
1936. Snow structures and ski fields. 555 pp., illus. London: MacMillan and Co., Ltd. [Reprinted Ed., 1962. Brussels: Jos. Adam.]

Swiss Federal Institute for Snow and Avalanche Research. [Schweitz. Eidg. Inst. für Schnee- und Lawinenforschung.]
1961. Lawinenverbau im Anbruchgebiet; Richtlinien für den permanenten Stutzverbau. Mitt. 15, Eidg. Insp. für Forstwesen, Bern. [Avalanche control in the starting zone; guidelines for the planning and design of permanent supporting structures.* Rep. 15. Fed. Inspector of Forests, Bern. Transl. by Hans Frutiger, and published as Sta. Paper 71, 60 pp., illus. 1962. Rocky Mountain Forest and Range Exp. Sta., U. S. Forest Serv., Ft. Collins, Colo.]
(Called the "guidelines" in this Manual.)

U. S. Forest Service.
1961. Snow avalanches: A handbook of forecasting and control measures. U. S. Dep. Agr. Agr. Handb. 194, 84 pp., illus.

______ 1964. Operation of the avalauncher--for use in avalanche control.* 21 pp., illus. U. S. Forest Serv. Region 5, San Francisco, Calif.

Voellmy, A.
1955. Über die Zerstörunskraft von Lawinen. Schweiz. Bauzeitung, Jahrg. 73, S. 159-165, 212-217, 246-249, 280-285. [On the destructive force of avalanches.* 1964. Transl. 2, 63 pp., illus. Alta Avalanche Study Center, Wasatch Nat. Forest, U. S. Forest Serv., Salt Lake City, Utah.]

Wechsberg, Joseph.
1958. Avalanche! 254 pp., illus. New York: Alfred A. Knopf, Inc.

APPENDIX

Structures of various types have been used in Europe for at least 300 years to protect highways, railroads, and inhabited areas from avalanches. The use of such structures in the United States and Canada is a fairly recent development. Many costly mistakes can be avoided if full advantage is taken of the experience gained in Europe.

The following articles, translated into English, cover several types of avalanche control structures, and give an insight into current practices in Switzerland and Austria.

The articles by Roch and Schwarz discuss what has been translated as "braking" structures. These are massive structures built on relatively flat places in the avalanche path to slow down and stop moving avalanches. Braking or retarding structures are usually earthen mounds, dams, or walls, but massive prestressed concrete tripods are also used. Both articles emphasize that such structures do not afford complete protection, and that they must be properly located to be effective.

In the third article, Frutiger and de Quervain discuss the relative merits and costs of avalanche sheds versus supporting structures for protecting highways and railways. Although it is not possible to translate the Swiss costs directly into American dollars, the ratio of the two types of control would probably be in the same order of magnitude.

POSSIBILITIES OF PROTECTION BY DEFLECTING OR BRAKING AVALANCHES, OR BY ARTIFICIAL RELEASE

by

A. Roch

(Possibilités de protection en déviant ou en freinant l'avalanche, ou par déclenchement artificiel. In Zum Winterdienst auf Strassen, S. 18-21. Eidg. Inst. für Schnee- und Lawinenforschung, Weissfluhjoch/Davos, Schweitz. Separatdruck aus Strasse und Verkehr, Nr. 1/1964. [In Report of winter road conditions, pp. 18-21, illus. Swiss Fed. Inst. for Snow and Avalanche Res. Reprinted from Streets and Traffic No. 1, 1964.])

Aside from the stabilization of the snow in the fracture zone, the best protection of a road against avalanches is a tunnel or a gallery (avalanche shed). Protection is then complete. But a mountain route all in tunnels is bound to be dull. Moreover, the construction of galleries is very expensive. If there is a possibility to deflect or slow the avalanche in its track, or to release it artificially, these practices will generally be less expensive, but they rarely give complete protection.

We want to study protection systems of this kind and to draw from them the lessons of what to do or not to do.

Deflection of the Avalanche.--To deflect an avalanche in motion is a very delicate operation because the mass of snow can easily pass over the structure destined to deflect it. One is limited, in general, to keeping the avalanche in its track and preventing it from spreading out onto the less steep parts of its course (fig. 17). Numerous walls have been constructed for that purpose in the Alps. In the Bedretto and the Conches Valley and in many villages, there are large walls designed to channel avalanches. At the Valais exit of the Loetschberg tunnel, at two places, large walls prevent an avalanche from spreading out and running over the railroad. These walls are parallel to the direction of flow of the snow.

At Platta Medel on the road to Lukmanier, a wall of prestressed concrete elements has been placed parallel to the direction of flow of an avalanche to protect a forest. That concrete wall was backfilled with dirt on the side opposite the avalanche. Unfortunately, the pillars built on the avalanche side could not resist the creep of the earth [fill]. They slowly leaned downward so much that the cement slabs threatened to pull out of the grooves in the pillars that support them. In order to remedy that fault, the framework of prestressed concrete was used as the back part of a form and a massive concrete wall was poured [against it]. The economy of the prestressed concrete construction was thus lost.

Deflecting walls forming an angle with the direction of the avalanche are rare. Such a wall is now under construction at Fionnay (Valais) to protect a water storage tank. It is sometimes advantageous to channel avalanches with deflection walls to make the snow pass over the roof of a gallery, which can then be shorter. Splitting wedges [tournes en coin] have also been placed on the slopes dominating the approach to a gallery so as to avoid obstructing the entrances.

The Braking and Stopping of Avalanches.--At the bottom of couloirs [gullies], in places where avalanches slow down naturally, large walls at right angles to the track have been built in an attempt to slow avalanches further, or to stop them. These experiments have often been disappointing. At Airolo in 1951, an enormous avalanche passed over a wall and only stopped after damaging 30 homes and killing 10 people. A wall placed at right angles to the direction of travel of an avalanche is not recommended except, for example, when built in a narrow ravine to dissipate the blast of a powder avalanche.

In Austria, the villages of Hötting, St. Niklaus, and Mühlau, in the outskirts of Innsbruck, are periodically menaced by avalanches coming from the mountains dominating the area north of Innsbruck (Innsbrucker Nordkette). The average vertical drop is 1,300 m. The avalanche fracture zones are immense, and each winter more woodland is carried away. Between 300 and 500 m. above the valley, the mountain slopes form a bench with an average inclination of 15°. Engineer W. Hassenteufel took advantage of this configuration to install braking structures. At first, these structures were built of concrete and masonry, backfilled with earth on the downhill side. It was later noticed that simple mounds of earth were sufficiently strong, did the same job, and above all, were less expensive. A number of mounds were placed in that zone. Little by little vegetation covered them and reinforced them. Their efficiency is excellent against avalanches of heavy snow. In fact, the masses of snow stopped on the mounds often increase their height and thus increase their effectiveness. As an experiment, braking mounds were placed on steeper slopes but their efficiency was low.

In Switzerland, the Vobag Company at Adliswil has cast tripods of prestressed concrete designed to resist 40 t/m^2. [These are tripods with two legs parallel to the contours and one leg down the fall line.] Twenty-four such tripods have been placed at Platta Medel above the road to the Lukmanier. Even though they are set very widely apart, their effect is good against ground avalanches of wet snow. In contrast, their effect is almost nil against the blast of powder avalanches. Furthermore, if the snow cover is deep, their effect is much reduced by their pyramidal form. The part that protrudes from the snow diminishes in volume as the depth of the snow cover increases. To remedy these defects, retarding tripods in the form of truncated pyramids with a trapezoidal surface perpendicular to the direction of the avalanche have been built at Andermatt (fig. 18). The facing on their upper side is concrete and they are filled with earth on the downhill side. Their efficiency should be good against powder avalanches too.

We should note again that 10 retarding tripods made by "Vobag" were placed at Fionnay (Valais) to slow an avalanche that threatened a reservoir and some buildings. Six of these tripods were completely broken by an avalanche carrying enormous blocks of rock.

Earthen mounds, as braking structures, were built in Switzerland above Brienzwiler, at a place where there was a terrace on the slope. In 1963, a powder avalanche passed over the mounds. It took out some woodland and stopped not far from the village. It was a close call, but catastrophe had, nevertheless, been avoided. As we mentioned, they do not afford complete protection.

Other mounds have been placed above Amden in the Canton of St. Gall and they have also been installed to protect the Trans-Canada highway [in British Columbia]. Experience shows us that:

Figure 17. Deflecting walls to channelize avalanches in the upper Valais. (Photo A. Roch)

a) Earthen mounds are effective against avalanches of wet snow flowing along the ground. Their effect is very slight against powder avalanches.
b) They must be located only in places where the avalanches are already slowed naturally by a reduction in slope gradient to less than 20°, or 35%.
c) The tripods are effective only if they are sufficiently close together so that the snow deflected from one will hit the next structure immediately. The effect is best if their summits present a reasonable surface area rather than a small triangle, as is the case if their form is pyramidal.

One should be careful in the use of braking structures. Yet, they should not be overlooked for they can mean an enormous savings in comparison to snow support structures in the starting zone and even in comparison to galleries or tunnels. In places where earthen mounds are to retard powder avalanches, an attempt should be made to place dams forming an angle with the direction of the avalanche and aligned so as to deflect the motion of the air and snow, and also to reduce the speed and power by producing turbulence.

Avalanche pits have been installed according to the configuration of the terrain. They are large depressions formed by a ditch on the valley side, depressions into which the avalanche tends to stop. Two such pits have been built on the Arzleralm above Innsbruck. The danger is that these pits can be filled by the first avalanches and the following ones can then pass over them. The dimensions of the depressions must be in proportion to the size of the fracture zone. At Arzleralm, the action of the pits is again reinforced by earthen mounds.

On the Spanish slope of the Pyrenees, enormous masonry barriers have been constructed in avalanche gullies. They are effective in that warm, dry climate.

It has not yet been tried to slow avalanches in a valley by increasing the sinuosity of the avalanche track. This could be done by accentuating the natural projections in the side of the ravine, or by walls along the flanks that would deflect the avalanche.

One could also break the blast of powder avalanches with deflection walls ranged in the middle of gullies, at the places where the blast is strongest. Dams in a ravine could also be very effective. Calculation of the force on these structures is very difficult because these avalanches produce enormous pressures. At Buera Valley in Zuoz, for example, where these measurements have been taken, the forces have exceeded 100 t/m^2.

Artificial Release of Avalanches.--The principle of artificially releasing avalanches with explosives or with gunfire for the protection of roads and communications can be extremely effective in some cases. It is used frequently to render ski trails safe, and on the Bernina Railroad explosives are used to release an avalanche named the "Fat Marianne." The method is practiced at Davos to release the avalanches of the Drusatscha which threaten the railroad as it approaches Davos. After each major snowfall, one to three times each winter, mortar shells are lobbed onto the mountain to try to release the snow. If the avalanche runs, the danger is removed. Usually it is not large enough to go all the way to the railroad, but the mountain is thus relieved of its snow and larger avalanches later in the season are avoided.

Following these practices, there is the risk of provoking a catastrophe like that of Zuoz in 1951. The avalanche which threatens the village, railroad, and highway was released too late by gunfire and carried away four houses and killed six people.

For gunfire to function well, it must be delegated to a local avalanche service, which decides when it should fire, basing judgment on the depth of the new snow, temperature, etc. This method is commonly used for the safety of access roads leading to construction sites in the mountains. It has rendered good service and has avoided accidents. In case of danger, the route is closed. One shoots, then one makes a pass with a snowplow to reestablish the thoroughfare.

In Switzerland, shooting is generally done with an 8.1 cm. mortar. They are distributed by the army which demands certain safety rules. Other means of artificial release utilize explosives, bombs from helicopters, rockets, and shots from bazookas and cannons. In the United States, at Alta and Squaw Valley, recoilless rifles placed on fixed mounts are used.

On the main highways, it is undesirable to stop the traffic to shoot and then to clean up. One would prefer the complete protection of putting the road into galleries or tunnels. But during catastrophic situations, the route will be blocked in any case. It is as well then to shoot in order to protect the road-clearing equipment. At certain spots, avalanches are dangerous only every 20 or 25 years. In these cases, the construction of a gallery cannot be justified; artificial release may then be very useful and will probably prevent catastrophes.

Fig. 18. Structures to slow down avalanches at Andermatt.

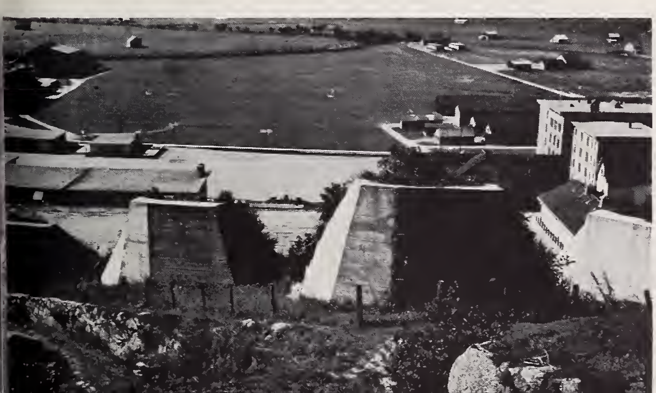

Fig. 19. Shot from a mortar to artificially release avalanches.

BRAKING STRUCTURES

by

W. Schwarz, Interlaken

(Bremsverbauungen. Schweiz. Z. Forstwesen, Nr. 1/1960, S. 41-54. [Swiss Forestry Magazine No. 1, 1960, pp. 41-54, illus.])

Structures built in the path of avalanches to "slow down the speed of avalanches and shorten their path through stemming their flow and through frictional action" are called Braking Structures.

According to the glossary of avalanche structures, we distinguish the following braking structures:

Catchdam or catchwall -- a dam or wall at right angles to the avalanche path, built to stop avalanches in the mound area.
Braking mounds -- mounds made of soil or stone.
Braking wedges -- concrete or stone wedge structures.

Catchdams and catchwalls have been built for more than 100 years. The village of Stuben in the Arlberg region has been protected since 1849 by a 6 m high catchwall. However, 5 to 6 m high catchwalls erected at the beginning of the century to protect the village of Airolo on the south slope of the Gotthard, from rockfall proved no protection against avalanches during the disastrous winter of 1950-51. Avalanches swept over these dams into the village, killing 10 persons and destroying 30 buildings.

A more recent practice is the use of mounds and wedges. These developed from the so-called "splitting wedge" concept. Splitting the avalanche into several branches on a field of mounds causes these branches to collide with each other. Furthermore, the snow is so directed that it impacts on the next row of mounds arranged in a checkerboard fashion.

The construction of such obstacles in the path of the avalanche interrupts the normal flow mechanics of the snow. The friction between moving snow and the gliding surface is increased and motion gradually slowed down.

Today the greatest amount of experience with braking structures is found in Austria. On the following pages we will describe some examples of Austrian mound construction.

Mühlau, a suburb of Innsbruck, situated at an elevation of 650 m, has suffered from the Arzlerarm avalanche in 1859, 1923, and heavy damage in 1935. Following the last disaster, eight staggered concrete bulwarks were constructed on a level part of the avalanche path at elevation 1025-1050 m. In addition, two catchbasins with catchdams each 9 m high were erected to collect any avalanches which might penetrate the bulwark field. These catchbasins were constructed at the elevation of 940 m.

Experience with this early construction showed that a similar braking effect could be obtained with earth mounds at a cost saving up to 90%. Two braking fields constructed later on the North chain of the Innsbruck range were made up exclusively of earth mounds. The Penzlehner construction consists of 27 mounds, the Allerheiligen field of 15 mounds. Mounds on the Allerheiligen field have a stone layer (without mortar) on the uphill side of each mound (see figure 2).

Another large Austrian avalanche braking structure made of earth was erected in the 1950's at Heiligenblut (province Kärnten).

Another type of construction must be mentioned here. This construction of Mühlau-Klamm near Innsbruck utilizes the energy-destroying principles used in stream control. Through a series of angled guiding dams and utilization of gullies existing in the avalanche path, it is possible to throw the avalanche alternately from one side to another. To further slow down the avalanche, a system of mounds was added at the bottom of the avalanche path.

Braking construction in Switzerland is of recent date. On the Lasa Alp (Tamina Valley near St. Gallen) seven mounds were built in 1956-57 to supplement existing structures.

At the foot of the Natschen-Grind Mountain near Andermatt, army barracks are protected by a row of eight concrete shell mounds filled with earth.

Braking bulwarks of a different type were erected in 1952 in the Graubünden Canton to protect the villages of Platta-Medels on the Lukmanier highway and in 1957 in Fionnay in the Untervallis.

These so-called "avalanche impact tripods" are made with prestressed concrete beams (made by Vobag in Adlisvil-Zurich) and constructed for a static pressure of 40 t/m^2. These tripods not only deflect avalanches but also cause them to be slowed down due to forcing of the snow between the beams of each tripod (see figure 5).

On the following pages we will describe the early history, planning, and construction of another Swiss braking structure on the Alpögli-Wilerhorn (Brienzwiler community, Bernese Oberland) which was completed in 1958. Avalanches originate on the south slope of the Wilerhorn (2004 m) and after traversing a series of horizontal ledges of 45-50° angle, reach a less steep area at elevation 1440 m on the Alpögli which is partly blocked by a natural barrier.

During the last 50 years several avalanches have broken over this natural barrier and through the protection of the forest, toward the village of Brienzwiler (population 600, elevation 702 m) which is located on the Brunig highway. In February of 1908, an avalanche opened up a 40 to 50 m wide clearing in the Grienwald forest below Alpögli. During the early 1940's, unusually large and dangerous avalanches occurred along the whole Brienzer range. This increase in avalanche activity coincides with the cessation of hay cutting on the slopes. The long stemmed grass, no longer mowed, increased the glide factor materially.

On March 8, 1945, a large avalanche fell on the Wilerhorn and continued on the west side of the 1908 clearing below the Alpögli. It destroyed 4000 m^3 of timber and opened a wide clearing down to the 800 m level. Other avalanches followed in 1946, 1952, 1954, and 1958 causing further damage to the forest stand and to farm sheds.

The danger to the village of Brienzwiler has grown to such an extent that defensive measures had to be planned. The question arose whether to erect barriers in the starting zone or construct a braking system. A barrier system would have to be spread over 4.75 hectares of which 0.75 was timbered. The area was also cut by deep gullies and steep vertical walls. These factors, as well as poor anchoring conditions and rockfall from the weathered peaks, would entail a cost of over 1 million Swiss francs for such a defense system. Only a fraction of this sum would be necessary for extensive braking structures in the Alpögli area. A pure braking field, however, would not have been sufficient in midwinter since the Wilerhorn produces dry powder avalanches at that time. Due to the lack of level ground, an arrangement of mounds in sufficient depth was also impossible. A combination of starting zone defenses and a braking mound system would eliminate the deficiencies of either system by solving the financial problem and overcoming the insufficiency of a pure mound system. At the same time such a combination of the two systems would still afford good protection for the village of Brienzwiler.

Based on the above conclusions, the plan for the defense project Alpögli-Wilerhorn covered an area of 2.2 hectares (of which 0.6 hectare was timbered) which included all slopes below the steep gullies producing dangerous powder avalanches. Through a barrier defense system in the starting zone, overburdening the mound system was avoided.

The cost of the project was as follows:

Reforestation	Fr.	50,250
Mound system		146,400
Barrier construction		478,000
Timber clearing		5,000
Road construction		18,000
Various costs		33,000
Unanticipated costs		59,150
Total	Fr.	790,000

The Alpögli mound system containing 23 mounds and having a total length of 170 m was constructed utilizing existing terrain advantages to the fullest. The catchdam was constructed to raise and lengthen the existing natural barrier and to extend above the steep Alpögli slopes. The existing natural catchbasin on the east side of the braking system was extended to the west side. The excavated material was used to construct the catchdam.

Avalanches are broken up on the mound field above the catchdam. The braking mounds are arranged in a staggered pattern in two rows (see figure 6). Utilizing flat spots on the slope, five additional mounds were erected on the east side of the mound field. The angle of the slope on which the lowest row of mounds stands is only 6-17°. The upper row of mounds is on a 17-26° slope and the uppermost three mounds are on a 26-30° slope. At slope inclinations of 30° we come close to the upper angle of friction for flowing snow which is between 32-38° and, therefore, limits the use of braking mounds. Basically, braking structures in the avalanche path should only be erected on flat transitions. It can be assumed that the upper limit of braking mound efficiency is at 30-35% of slope inclination. None of the Austrian mound fields at Arzleralm, Penzenlehner, and Allerheiligenhof are on slopes above 35%. On the Alpögli the three uppermost mounds are on a 50% slope, but they have been built as an avalanche splitting wedge rather than for braking purposes. After splitting the avalanche, one arm is directed toward the double row of mounds on the west side of the field, the other arm flows toward the flat transition on the east side.

The height of the braking mounds was planned according to the expected snow mass. On the Alpögli, the mounds were constructed with a vertical height H of 5.0 m and the uppermost three mounds with a height of 4.0 m. An increase in the effective [working] height of the mounds was achieved by increasing the height of the mounds coinciding with the decrease of the slope angle.

The pressure of the avalanching snow grows proportionately to the square of the avalanche's speed. It is, therefore, expedient to construct mounds relatively low at the upper level of a field and increase the height of successive mounds.

The arrangement of the mounds as already mentioned is staggered as on a checkerboard. A channeling of avalanches is avoided therefore, by filling of the gaps with successive mounds.

Distance between mounds on the Innsbruck North Range is approximately 15 m from base to base. This distance also approximates the diameter of the mound at its base.

On the Alpögli, the effective working distance was kept much smaller at 5.5 m, which results in a center-to-center distance of 20 m. This denser arrangement of mounds results in a lesser impact force per single mound than in the Austrian construction. This was not only done to increase the efficiency of the mound system, but also because of the lack of space to accommodate the mound system.

The distance between mounds in the direction the avalanche travels should depend on the heights of the mounds, the angle of the mound face, and the slope angle. Mound density depends on the availability of earth on the site. Availability of local material for building of mounds has another advantage. Cuts made on the uphill side of mounds consume additional avalanche energy. Austrian systems take the fill in a semicircle from both sides and from the uphill side of the mound. On the Alpögli field, because of the density of the mounds, fill was taken from the uphill side only. This produced a depression 3 to 7 m wide above each row of mounds. Fill taken from the downslope side of the lowest row of mounds created a catchbasin 15-40 m wide and a catchdam 5-7 m high.

The cone profile for the mounds was chosen with a natural face angle ratio of approximately 4:5. The cone faces were seeded with grass or with low-growing shrubs. The Innsbruck North Range mound system was covered on the uphill side with stones. In Heiligenblut (Kärnten) the total cone face was covered with bricks.

The volume of a mound can be calculated (regardless of cone angle) as a frustrum, with the following formula:

$$V = \frac{h \times a \times b}{3} \times \pi$$

where

h = height of the mound measured vertically to the slope from the base to the tip of the cone,
a = half of the largest base diameter, and
b = half of the smallest base diameter.

Following this formula it was found that the 5 m Alpögli mounds had a volume from 320-580 m^3. This wide spread in volume is due to the variation in slope angle.

Construction of the Alpögli mound system was done with one to three traxcavators which had a shovel capacity of 1.25 to 2.00 m^3. Construction time was 2 months. Five men were steadily used for all grading work on the mounds, the catchdam, and the field edges.

Loose, gravelly on-site material was used for the mounds (9,850 m^3 at Sw. fr. 3.10 per m^3), and for the catchdam (9,100 m^3 at Sw. fr. 2.80 per m^3).

After removal of the humus overburden and terracing of the slope with bulldozers, the excellent permeable material was used directly for the mounds and the dam without any further preparation.

Total cost of the project with approximate earth removal of 19,000 m^3 was 85,000 Swiss francs. This amount includes a 900 m nonpaved approach road, and widening of existing roads to accommodate machinery, as well as other items on the construction site.

This summer, work was begun to install a stone covering on the uphill side of the more exposed mounds. The price for the installation is 12.0 Sw. fr. per square meter of cone surface. This cost is not included in the above-mentioned total construction bid of 85,000 Sw. fr.

The above discussion on the examples of braking systems both here [in Switzerland] and abroad brings to mind some basic questions regarding avalanche structures which were asked by the late Chief Forester Dr. Hess:

Figure 1. Bulwarks (4 m high) on the Arzleralm. Catchdam is below the braking system.

1. Could the objects which are to be protected from avalanches be moved at less cost than it takes to build protective structures?
2. Is there some way by which villages and buildings could be protected directly (with bulwarks or through building on elevated ground)?
3. Would it not be more economical to protect highways and railroads with sheds and tunnels rather than with costly barriers in the starting zone?
4. Would diversion walls or dams be as efficient as structures in the starting zone?

Mound construction can certainly be included in question 4. Possible application of mounds in Switzerland is far greater than could be assumed by the number of mound defenses built so far. Protection against avalanches was too often solved by the standard system of structures in the starting zone. In addition, certain resistance is encountered from the local population which has little faith in the still unknown mound system. Also, building of such systems would require that these people give up some of their precious level and producing land. But these considerations should not lead to the exclusion of mound construction, particularly since such systems are far less expensive than the erection of defense systems in the starting zone.

Figure 5. Avalanche tripods near Fionnay; upper part arranged as a diversion wall.

Figure 2. The Penzlehner mound system with stone facing on the uphill side.

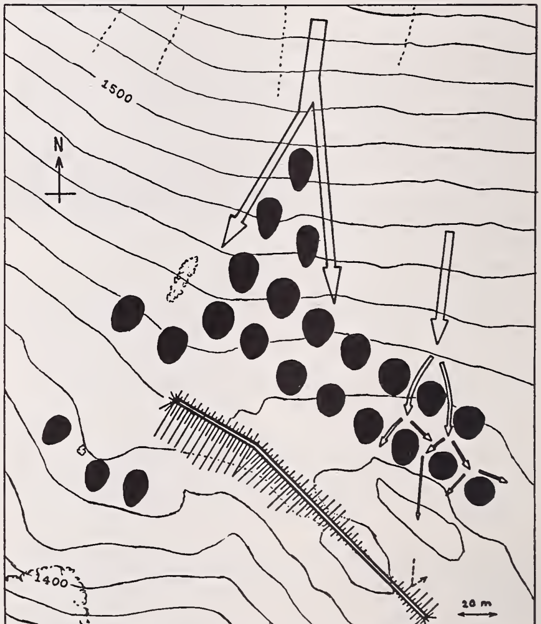

Figure 6. Location sketch of the Alpögli-Wilerhorn braking system.

Figure 4. A combination defense structure of: (2 and 3) guiding dams; (1 and 4) mounds; and (5) a natural barrier, on the Mühlauer-Klamm.

Figure 3. The Allergeiligen mound field with guiding dams to contain avalanches in their normal path.

Figure 8. Construction mounds with conveyors at Heiligenblut, face angle 1:1.

Figure 7. East side view of the Alpögli defense systems.

SUPPORTING STRUCTURES OR GALLERIES?

by

Hans Frutiger and M. de Quervain

(Stutzverbau oder Galerie? In Zum Winterdienst auf Strassen, S. 17-18. Eidg. Inst. für Schnee-und Lawinenforschung, Weissfluhjoch/ Davos, Schweitz. Separatdruck aus Strasse und Verkehr, Nr. 1/1964. [In Report of winter road conditions, pp. 17-18, illus. Swiss Fed. Inst. for Snow and Avalanche Res. Reprinted from Streets and Traffic, No. 1, 1964.])

The question of whether to build supporting structures or a gallery (avalanche shed) is usually settled by the cost of the two types of structures. This article then will be an observation and a comparison of the costs of the two systems. Since not many galleries have been built to protect roads, and since most of the gallery building is still in the planning stage, it is difficult to present usable material. To compare the cost of the two systems, the figures from galleries built by the railroad will also be used. In using these figures, one must notice the dates of the expenditures.

According to H. Conrad, the cost of the galleries built in 1949 on the Rhaetian Railroad was 1,440 Swiss francs per running meter. The galleries built by the Austrian Federal Railroads in the years 1954 and 1955 cost 26,000 shillings per meter, which under the rate of exchange of 16.80 costs about 1,550 Swiss francs per running meter. In the years 1954 and 1955, five galleries were built for the protection of the so-called tourist highways. The widths of these galleries were 5.5 meters, increasing to 6.6 meters in the curves. The cost was between 3,890 and 4,600 Swiss francs per running meter.

The widths of the galleries on alpine roads leading to important passes should be from 7.0 to 8.0 meters. They will cost 5,000 Swiss francs per running meter.

The width of third class national roads is at least 8.0 meters and as a rule 9.0 meters. For these roads, it is almost imperative that galleries costing 5,000 Swiss francs per meter be provided. If we make a comparison of the cost of building galleries on the tourist highways, we will have to concede a cost of 5,000 to 8,000 Swiss francs per running meter.

The cost of building supporting structures is listed and discussed elsewhere. In comparing the cost of building these two systems, one has to take into consideration the terrain conditions and the size of the fracture zone of the avalanche in comparison to the length of road to be protected. In the end, however, the deciding factor will be the question of cost.

It will be best to give examples first of situations in which one or the other system will be, without question, the best solution and then to discuss the borderline cases. It is not profitable to build a gallery for small avalanches, in particular those which originate on short, smooth, nonchannelized slopes and which therefore cover a long stretch of road. This type of avalanche brings little snow and also little debris. Often they merely are bank slides which do not offer any particular danger to traffic. If the possibility of afforestation exists, supporting structures will be the more desirable solution.

Other conditions, however, have to be considered. It is possible that in some areas there may be hindrances other than avalanches obstructing a stretch of road, for example, heavy snowdrifts. In this case, the gallery will not only protect the road from avalanches but also from the drifting snow. The gallery will be the best solution for an avalanche whose catchment basin has reached a certain size, but whose track is narrow so that only a short stretch of road is touched by the avalanche. There are, however, limitations here also. It may be possible that a road will cross the same avalanche path several different times which, of course, would necessitate building a gallery at each of these crossings. In this type of situation, as well as in the case of protecting forests or settlements, supporting structures would be the more advantageous or even the only solution.

If the road is located on a steep slope and if the avalanches are channelized, as a rule, the average length of the road which will be in danger of avalanches is from 50 to 70 meters. If, however, the stretch of road is located on a flat area, and in particular if it is located on alluvial fans, the length of road being endangered will be greatly increased. On these cone-shaped runout zones, it is often possible for the avalanche to divide and have damaging side effects and greatly increase the stretch of road which must be protected. Under these unfavorable conditions, galleries have to be more than 100 meters in length. For the purposes of this discussion, we will take 200 meters as the standard length of a gallery.

In order to formulate a comparison, all of the details have to be carefully analyzed. Here is an example in the case of an unconfined avalanche. Let's assume that the cost of building satisfactory supporting structures is 0.6 million Swiss francs per hectare, while the gallery for a main highway costs 5,000 Swiss francs per running meter. For protection against this unconfined avalanche which originates on a short incline, the gallery will be as long as the fracture zone is wide. In order to cover a fracture zone 100 meters wide, it will take a gallery 100 meters long or 0.5 million Swiss francs. The fracture zone can be no more than 80 meters long if supporting structures are to compare favorably in cost with a gallery. If the slope to be built up by supporting structures is longer than 80 meters, the supporting structures will be more expensive than the gallery.

In the case of a large, channelized avalanche, the gallery is undoubtedly more favorable. Assuming a fracture zone of 200 by 200 meters, requiring supporting structures over 4 hectares and a gallery 70 meters long, the comparative cost would be 2.4 million Swiss francs to 0.35 million Swiss francs, or 7 to 1. In this case, only when the length of the gallery is 480 meters or more would the supporting structures become more favorable. The cost of the two systems again compares favorably in a situation where it is necessary to build supporting structures over 2 hectares and a gallery length of 200 meters.

Other things, not necessarily of a financial nature, must also be taken into consideration when deciding which of these two systems to build. Supporting structures are more favorable when they can serve other purposes besides the protection of a road; for example, protection of settlements and forest industries, et cetera. Maintenance cost of supporting structures is fairly high; a gallery, on the other hand, requires relatively little maintenance. One disadvantage of the gallery could be a reduction of travel comfort in summer.

Finally, it is still maintained that the decision whether to build supporting structures or a gallery can only be decided and handled as individual problems depending on the specific circumstances.

[Translator's note: The break-even point seems to be about 100 meters of gallery per hectare of supporting structures, or 130 feet of gallery per acre of supporting structures. The official rate of exchange is about 4 Swiss francs per dollar. A direct translation of costs is not possible, however, because of differences in construction and labor costs.]

Frutiger, Hans, and Martinelli, M. Jr.
1966. A manual for planning structural control of avalanches. U. S. Forest Serv. Res. Paper RM-19, 68 pp., illus. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado.

Classifies avalanches for avalanche control work. Identifies the important parts of an avalanche area. Discusses the following types of avalanche control structures: Supporting structures and wind baffles in the starting zone; diverting, guiding, retarding, and catching structures in the track; and direct-protection structures in the runout zone. Outlines the field observations and design specifications necessary for planning an avalanche control project, and develops a control plan for a specific avalanche.

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Frutiger, Hans, and Martinelli, M. Jr.
1966. A manual for planning structural control of avalanches. U. S. Forest Service Res. Paper RM-19, 68 pp., illus.

ERRATA

PREFACE: Snow density is expressed... Should read--

$0.100\ t/m^3 = 100\ Kg/m^3 = 0.10\ g/cm^3 = 10$ percent.

FOOTNOTES: Footnote 8 on page 15 should be footnote 14 on page 42; footnote 14 should be footnote 8.

On page 46, last line: footnote number should be 15 instead of 14.

FIGURES: Figure 25, page 25, Zone 1: Change (snow baffles) to (wind baffles).
Figure 38(Nomograph 1): In the line drawing of the explanatory portion, change f_e to f_C, and S'_a to S'_Q.

NOMOGRAPHS 1-4 (For use with "A Manual for Planning Structural Control of Avalanches," Res. Paper RM-19, and "Avalanche Control in the Starting Zone," Sta. Paper 71 -- referred to as the Guidelines.

Graphic and tabular solutions are given here for certain of the formulas used in computing the components of the snow pressure forces. The numbers in parentheses refer to the formulas given in the Guidelines. All formulas were developed for the metric system. Substitutions into them have been made by that system, then converted to U. S. equivalents.

NOMOGRAPH 1 represents the following equations:

$S'_N = 0.10 \times H^2 \times N \times f_C$ (t/m') [Art. 52,1]

$S'_Q = S'_N \times \frac{a}{N \times tg\psi}$ (t/m') [Art. 52,2]

S'_N = component of snow pressure parallel to the slope per unit length of the supporting plane

S'_Q = component of snow pressure perpendicular to the slope per unit length of the supporting plane

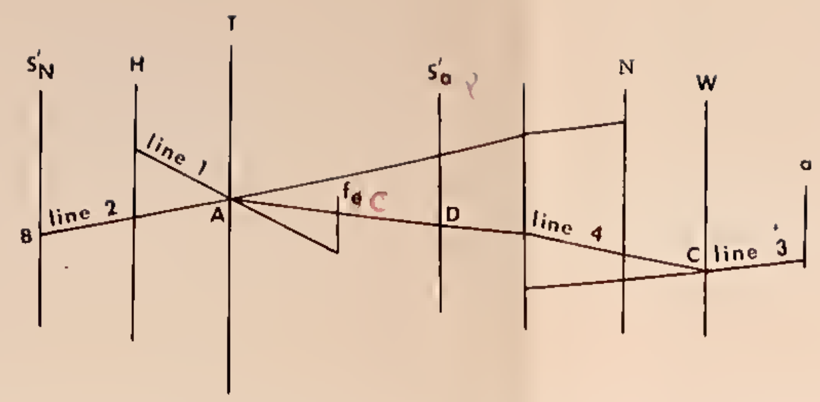
H = extreme snow depth, measured vertically, at the site of the structure

N = glide factor

f_C = altitude factor

a = ratio that varies between 0.2 and 0.5, depending on the kind of snow

$tg\psi$ = tangent of the angle of the slope



To solve for S'_N, draw line 1 connecting known values of H and f_C, thus locating point A on the T scale. Then draw line 2 from a known value of N through point A to locate point B on the S'_N scale.

To solve for S'_Q, draw line 3 connecting the a and ψ scales to locate point C on the W scale. Then draw a line connecting points A and C. This line will cross the S'_Q scale at point D, which represents the required value of S'_Q.

NOMOGRAPH 1

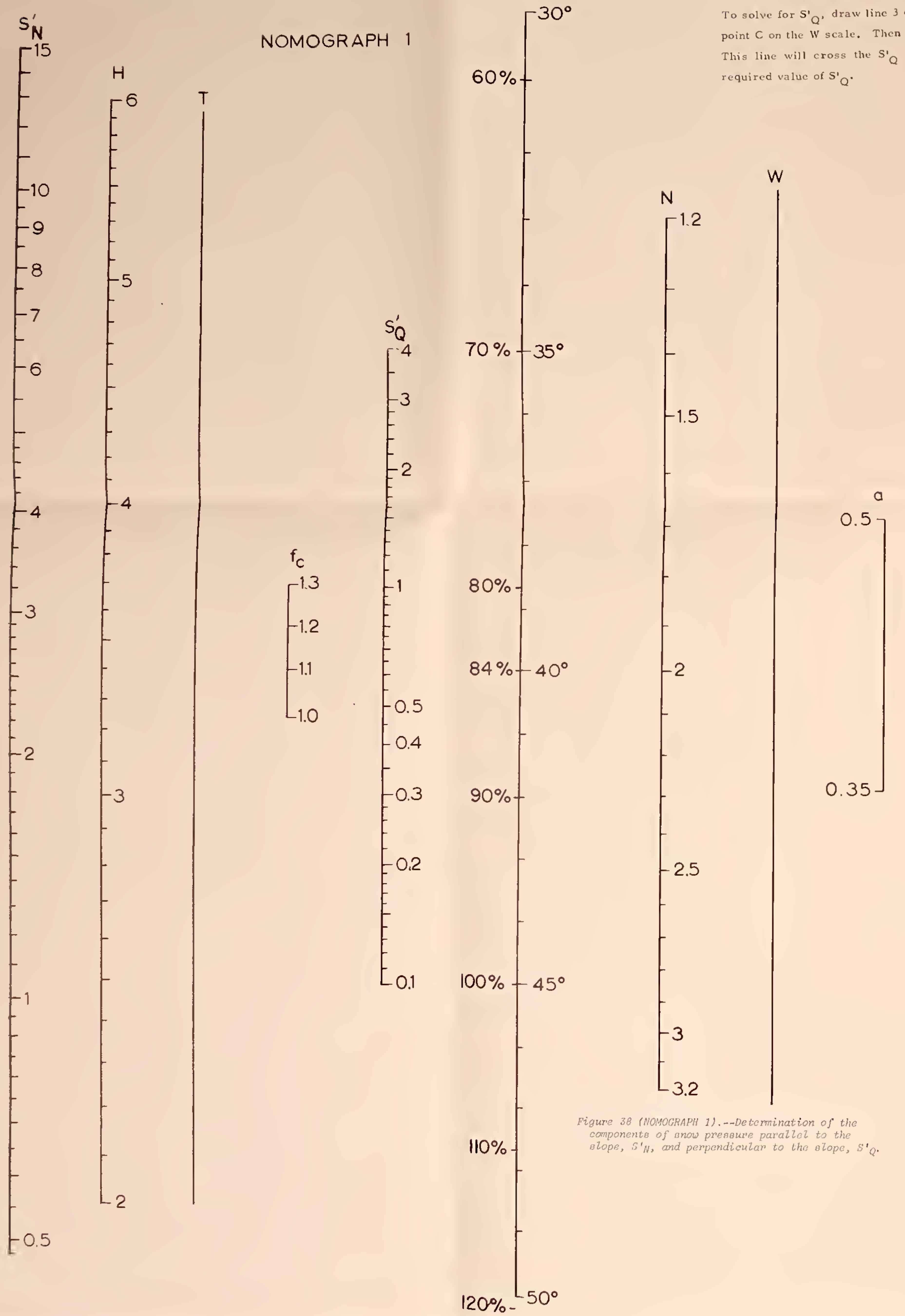


Figure 38 (NOMOGRAPH 1).--Determination of the components of snow pressure parallel to the slope, S'_N, and perpendicular to the slope, S'_Q.

NOMOGRAPH 2 represents the following equations:

$G'_N = 0.4 \times H^2 \times \sin\psi \times (\cos\psi)^2$

$G'_Q = 0.4 \times H^2 \times (\cos\psi)^3$

$G' = 0.15 \times D^2 \times tg\,\varrho$ (t/m') [Art. 29; 52,4]

G' = weight in t/m' of that snow prism which is confined by the supporting plane and a plane perpendicular to the slope at the foot of the supporting plane

G'_N = components of G' parallel to the slope, in t/m'

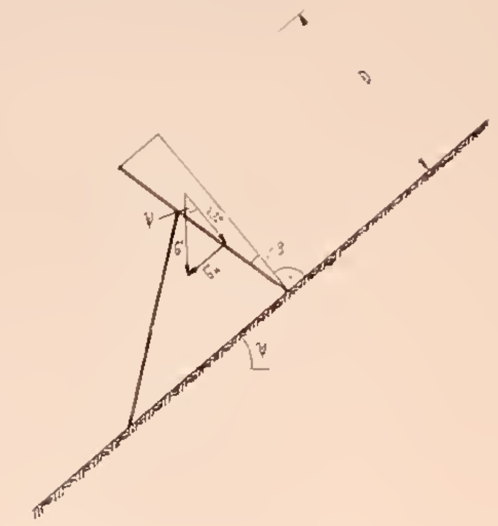
G'_Q = components of G' perpendicular to the slope, in t/m'

D = thickness of snow cover, in meters, measured perpendicular to the slope

H = extreme snow depth, measured vertically, at the site of the structure

ψ = angle of the slope in degrees

ϱ = angle between the supporting plane and a plane perpendicular to the slope at the foot of the supporting plane



To solve either of these equations, draw a line connecting a known value of H and a known value of ψ. It will be noted that there are ψ_N and ψ_Q scales. The required value of G'_N will be on the line connecting the H and the ψ_N scales, while the value of G'_Q will be on the line connecting the H and the ψ_Q scales.

NOMOGRAPH 2

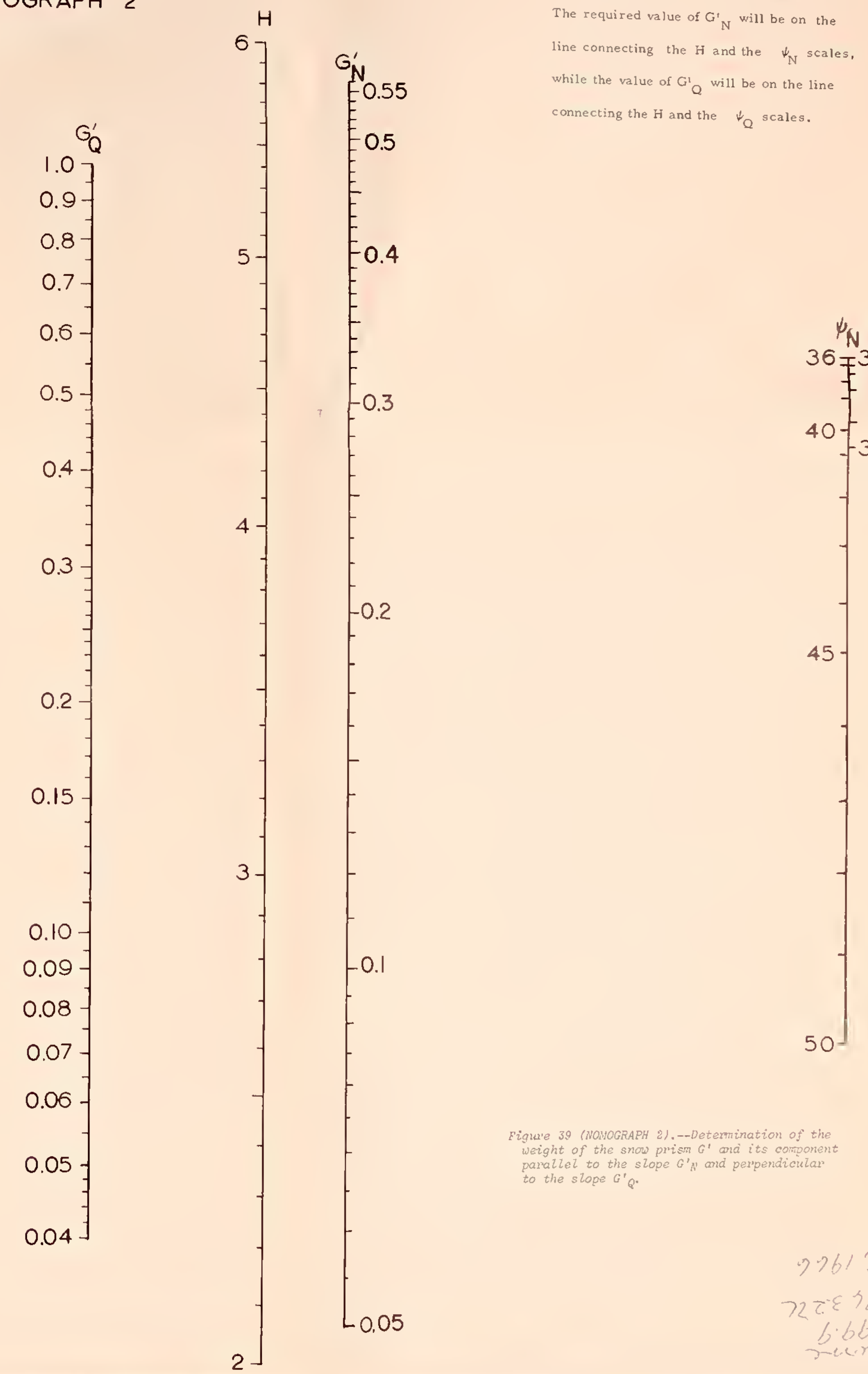


Figure 39 (NOMOGRAPH 2).--Determination of the weight of the snow prism G' and its component parallel to the slope G'_N and perpendicular to the slope G'_Q.

NOMOGRAPH 3 represents the following equation:

$$R' = \sqrt{R'^{2}_{N} + R'^{2}_{Q}} \qquad (t/m') \qquad [Art.\ 31,3]$$

where

$R'_N = S'_N + G'_N$ [Art. 31,1]

$R'_Q = S'_Q + G'_Q$ [Art. 31,2]

R' = resultant force

S'_N = component of snow pressure parallel to the slope per unit length of the supporting plane

S'_Q = component of snow pressure perpendicular to the slope per unit length of the supporting plane

G'_N = components of G' parallel to the slope, in t/m'

G'_Q = components of G' perpendicular to the slope, in t/m'

Nomograph 3 is a simple three-scale nomograph. It is solved by drawing a line between known values on the outer scales. The point where this line crosses the center scale is the required value.

NOMOGRAPH 3

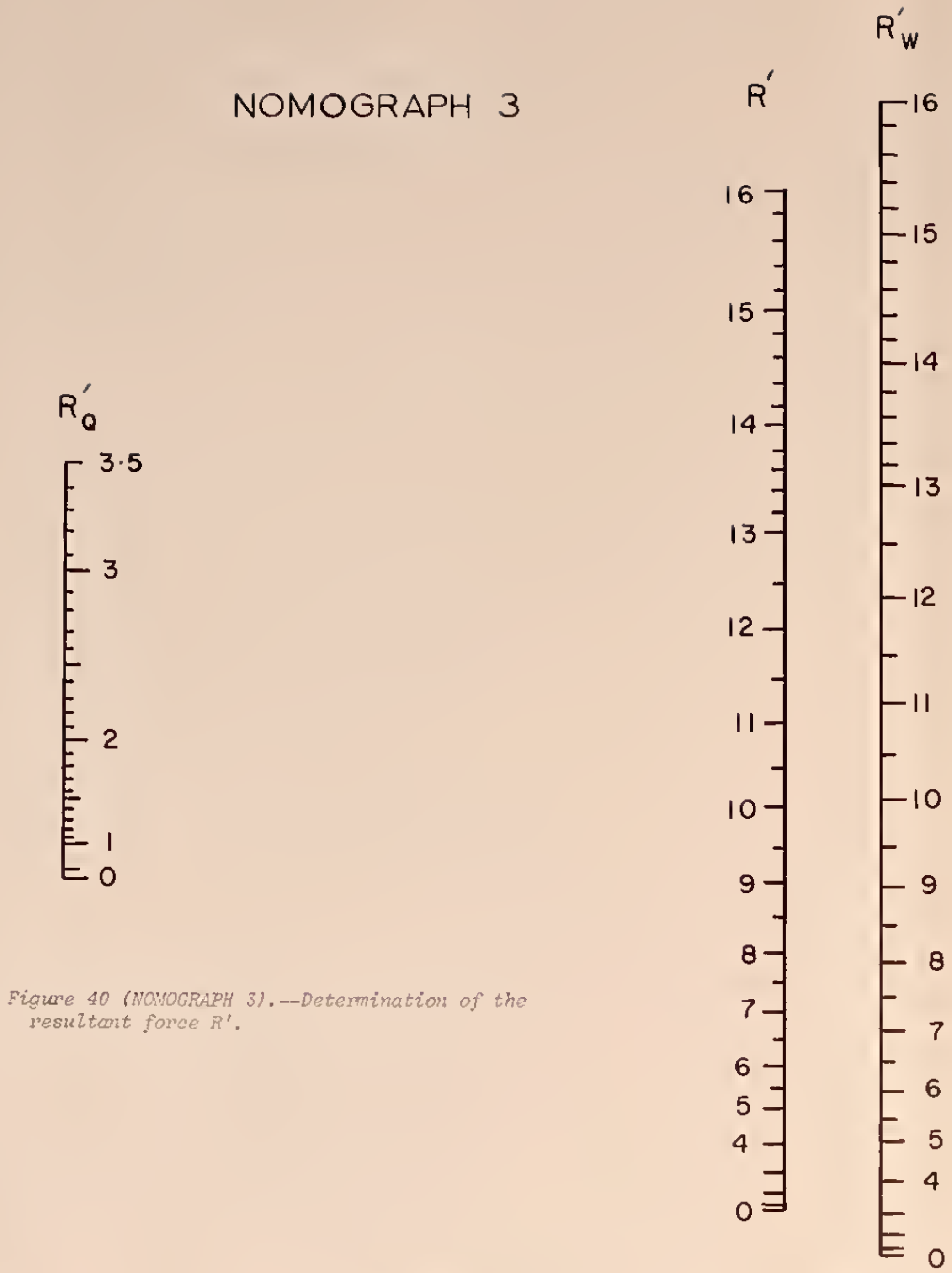


Figure 40 (NOMOGRAPH 3).--Determination of the resultant force R'.

NOMOGRAPH 4 gives the angle of inclination of the resultant force R'; that is, the angle between R' and the direction parallel to the slope -- [Art. 31,5; 52,3]

Nomograph 4 is also a simple three-scale nomograph. It is solved by drawing a line between known values on the outer scales. The point where this line crosses the center scale is the required value.

NOMOGRAPH 4

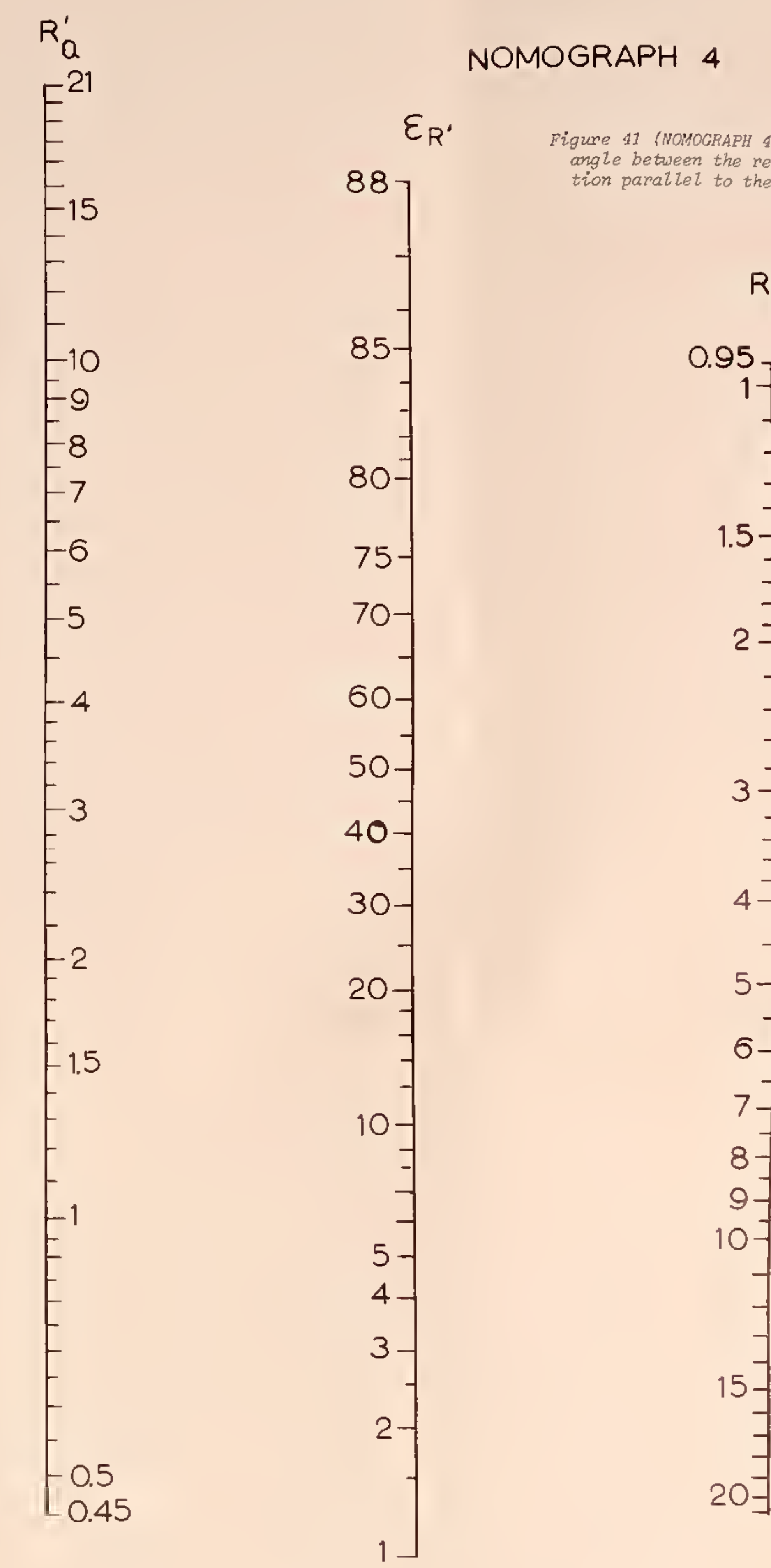


Figure 41 (NOMOGRAPH 4).--Determination of the angle between the resultant R' and the direction parallel to the slope.

TABLE 4.--ϵ_R and the multiplication factor, f, used in the formula $R' = \frac{H^2}{5} \times f$, to calculate resultant snow pressure, R', for an infinitely long wall; includes eight values of glide factor, N

R' = resultant snow pressure force for a continuous structure (no end effects)

H = snow depth, in meters, measured vertically at the structure site

f = multiplication factor N = glide factor

ϵ_R = angle between R' and the direction parallel to the slope (inclination of R')

Altitude of control area (meters above sea level) with altitude factor, f_C	Angle of slope ψ	N = 1.2		N = 1.3		N = 1.6		N = 1.8		N = 2.0		N = 2.4		N = 2.6		N = 3.2	
		f	ϵ_R	f	ϵ_R	f	ϵ_R	f	ϵ_R	f	ϵ_R	f	ϵ_R	f	ϵ_R	f	ϵ_R
	Percent		Degrees		Degrees		Degrees		Degrees		Degrees		Degrees		Degrees		Degrees
	60	0.79	32	0.84	30	0.97	25	1.06	23	1.15	21	1.34	18	1.44	17	1.73	14
0 - 1,500	70	.77	28	.81	26	.95	22	1.04	20	1.14	19	1.33	16	1.43	15	1.72	12
	84	.74	24	.78	22	.93	19	1.02	17	1.12	16	1.31	13	1.41	12	1.70	10
f_C = 1.00	100	.72	20	.76	19	.91	16	1.00	14	1.10	13	1.30	11	1.39	10	1.69	8
	120	.69	16	.74	14	.88	12	.98	11	1.08	10	1.28	8	1.38	8	1.67	6
	60	.82	32	.87	30	1.00	25	1.10	23	1.20	21	1.39	18	1.49	17	1.79	14
1,500 - 1,700	70	.79	28	.84	26	.98	22	1.08	20	1.18	18	1.38	16	1.48	15	1.78	12
	84	.76	24	.81	22	.96	19	1.06	17	1.16	15	1.36	13	1.46	12	1.77	10
f_C = 1.04	100	.74	20	.79	19	.94	16	1.04	14	1.14	13	1.34	11	1.45	10	1.75	8
	120	.71	15	.76	14	.92	12	1.02	11	1.12	10	1.33	8	1.43	8	1.74	6
	60	.86	31	.91	29	1.05	25	1.16	23	1.26	27	1.47	18	1.57	17	1.89	14
1,700 - 2,000	70	.83	28	.88	26	1.03	22	1.14	20	1.24	18	1.45	15	1.56	14	1.88	12
	84	.80	23	.85	22	1.01	18	1.11	17	1.22	15	1.43	13	1.54	12	1.86	10
f_C = 1.10	100	.78	20	.83	19	.99	16	1.09	14	1.20	13	1.42	11	1.53	10	1.85	8
	120	.75	15	.80	14	.96	12	1.07	11	1.18	10	1.40	8	1.51	8	1.83	6
	60	.93	31	.98	29	1.14	25	1.25	22	1.36	20	1.59	17	1.70	16	2.05	13
2,000 - 2,500	70	.90	27	.95	26	1.12	22	1.23	19	1.34	18	1.57	15	1.69	14	2.04	12
	84	.87	23	.92	22	1.09	18	1.20	16	1.32	15	1.55	13	1.67	12	2.02	10
f_C = 1.20	100	.84	20	.90	18	1.07	15	1.19	14	1.30	13	1.54	11	1.66	10	2.01	8
	120	.81	15	.87	14	1.05	12	1.16	11	1.28	10	1.52	8	1.64	8	2.00	6
	60	.99	31	1.05	29	1.23	24	1.34	22	1.47	20	1.71	17	1.84	16	2.21	13
2,500 - 3,000	70	.96	27	1.02	25	1.20	21	1.32	19	1.44	18	1.69	15	1.82	14	2.21	11
	84	.93	23	.99	22	1.17	18	1.30	16	1.42	15	1.68	12	1.80	12	2.19	10
f_C = 1.30	100	.90	19	.97	18	1.15	15	1.28	14	1.40	12	1.66	10	1.79	10	2.17	8
	120	.87	15	.94	14	1.13	12	1.25	10	1.38	9	1.64	8	1.77	7	2.16	6

EXAMPLE (see Sects. 12.22 and 12.222):

Vertical snow depth . . . . H = 5.5 m

Glide factor . . . . N = 2.4

Altitude factor. . . . . . f_C = 1.3

Angle of the slope. . . . . ψ = 76%

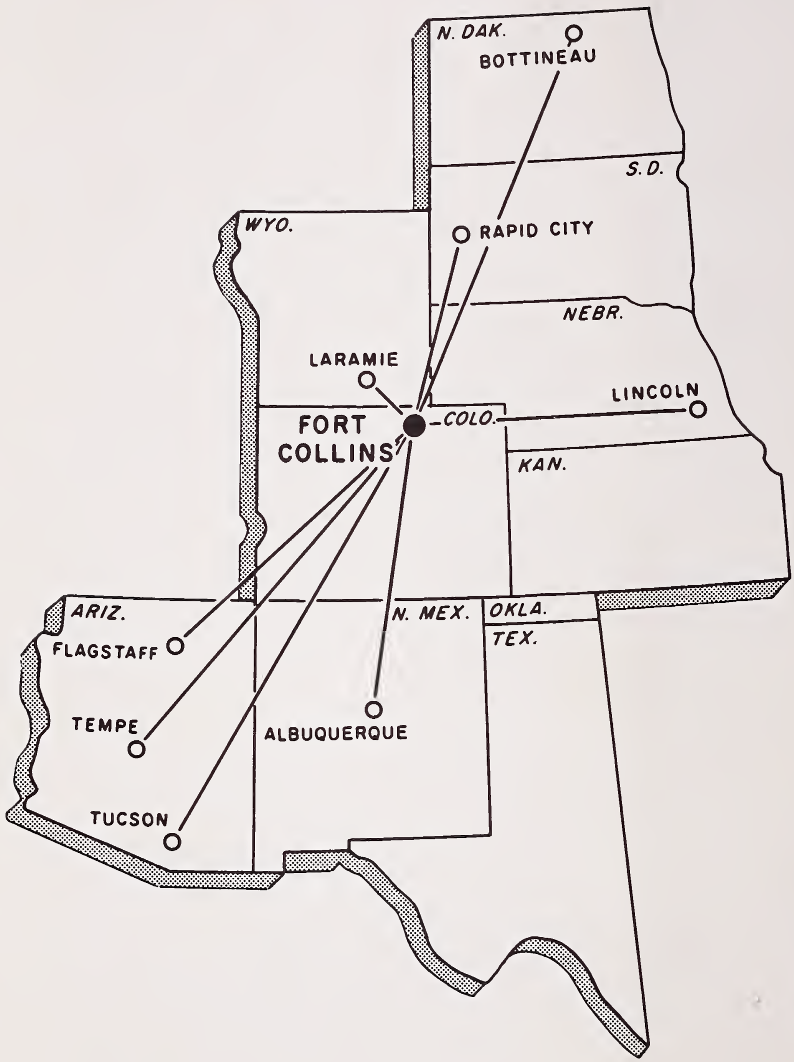
Tilt of the grate . . . . . ϱ = 15°

From table 4, the factor f is found to lie between 1.68 and 1.69; it is nearer to 1.69.

ϵ_R is between 12° and 15°; it is nearer to 15°.

Therefore:

$$R = \frac{5.5^2}{5} \times 1.69 = 10.2\ t/m' \qquad \epsilon_R = 14°$$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